IAEA SAFETY STANDARDS SERIES

Flood Hazard for Nuclear Power Plants on Coastal and River Sites

SAFETY GUIDE

No. NS-G-3.5

IAEA
International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish standards of safety for protection against ionizing radiation and to provide for the application of these standards to peaceful nuclear activities.

The regulatory related publications by means of which the IAEA establishes safety standards and measures are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety, and also general safety (that is, of relevance in two or more of the four areas), and the categories within it are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides.**

Safety Fundamentals (blue lettering) present basic objectives, concepts and principles of safety and protection in the development and application of nuclear energy for peaceful purposes.

Safety Requirements (red lettering) establish the requirements that must be met to ensure safety. These requirements, which are expressed as ‘shall’ statements, are governed by the objectives and principles presented in the Safety Fundamentals.

Safety Guides (green lettering) recommend actions, conditions or procedures for meeting safety requirements. Recommendations in Safety Guides are expressed as ‘should’ statements, with the implication that it is necessary to take the measures recommended or equivalent alternative measures to comply with the requirements.

The IAEA’s safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA.

Information on the IAEA’s safety standards programme (including editions in languages other than English) is available at the IAEA Internet site

www-ns.iaea.org/standards/

or on request to the Safety Co-ordination Section, IAEA, P.O. Box 100, A-1400 Vienna, Austria.

OTHER SAFETY RELATED PUBLICATIONS

Under the terms of Articles III and VIII.C of its Statute, the IAEA makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety and protection in nuclear activities are issued in other series, in particular the **IAEA Safety Reports Series**, as informational publications. Safety Reports may describe good practices and give practical examples and detailed methods that can be used to meet safety requirements. They do not establish requirements or make recommendations.

Other IAEA series that include safety related publications are the **Technical Reports Series,** the **Radiological Assessment Reports Series,** the **INSAG Series, the TECDOC Series**, the **Provisional Safety Standards Series**, the **Training Course Series,** the **IAEA Services Series** and the **Computer Manual Series**, and **Practical Radiation Safety Manuals** and **Practical Radiation Technical Manuals**. The IAEA also issues reports on radiological accidents and other special publications.

FLOOD HAZARD FOR NUCLEAR POWER PLANTS ON COASTAL AND RIVER SITES

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHILE
CHINA
COLOMBIA
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SERBIA AND MONTENEGRO
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

Printed by the IAEA in Austria
December 2003
STI/PUB/1170

SAFETY STANDARDS SERIES No. NS-G-3.5

FLOOD HAZARD FOR NUCLEAR POWER PLANTS ON COASTAL AND RIVER SITES

SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2003

IAEA Library Cataloguing in Publication Data

Flood hazard for nuclear power plants on coastal and river sites : safety guide. — Vienna : International Atomic Energy Agency, 2003.
p. ; 24 cm. — (Proceedings series, ISSN 1020–525X ; no. NS-G-3.5)
STI/PUB/1170
ISBN 92–0–112803–7
Includes bibliographical references.

1. Nuclear power plants—Natural disaster effects. 2. Flood damage. I. International Atomic Energy Agency. II. Series.

IAEAL 03–00339

FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide provides recommendations on how to meet the requirements established in the Safety Requirements publication on Site Evaluation for Nuclear Installations [1] in respect of the flood hazard to be used in site evaluation for nuclear power plants on coastal and river sites. Measures for the protection of nuclear power plant sites against floods and the strategy for monitoring sites are also discussed.

1.2. This Safety Guide is the first revision of and supersedes two Safety Guides dealing with flood hazards on river sites and on coastal sites respectively and originally issued under the IAEA's safety standards programme in 1983.[1]

1.3. The two former Safety Guides have been merged in this revised version for the following reasons:

(1) Flood hazards on river sites and on coastal sites give rise to similar actions by plant designers for the protection of both the site and the plant;

(2) The meteorological causes of the phenomena observed on sites of both kinds are often the same and the phenomena very similar;

(3) In many cases the effects of the marine environment and the river environment on the same site can be combined: it is therefore convenient to have a joint treatment.

1.4. New sections have been developed on the basis of a detailed review of recent years of operation of nuclear power plants around the world. These relate mainly to:

---

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Design Basis Flood for Nuclear Power Plants on River Sites, Safety Series No. 50-SG-S10A, IAEA, Vienna (1983); Design Basis Flood for Nuclear Power Plants on Coastal Sites, Safety Series No. 50-SG-S10B, IAEA, Vienna (1983).

- Requirements for input data in term of sufficiency and reliability, oriented towards application in States with limited historical background in the subject and therefore with different technical approaches (e.g. a deterministic approach as opposed to a probabilistic approach);
- Monitoring requirements and techniques in connection with warning systems, with all the implications in terms of reliability and the size of the area monitored, and therefore competences;
- Mechanisms for updating of the hazard analysis with reference to very fast modifications in the intrinsic properties relating to both precipitation (intensity, area and frequency) and the basin (drainage, population, water storage and artificial obstacles).

1.5. Other Safety Guides relating to site evaluation present discussion on flood related events — for earthquake induced tsunamis, flood induced effects on foundations, procedures for the site survey, and precipitation and cyclonic wind hazard — and are thus complementary to this Safety Guide [2–4].

OBJECTIVE

1.6. The purpose of the present Safety Guide is to provide recommendations relating to the evaluation of the flood hazard for a nuclear power plant on a coastal or river site so as to enable the identification of hazardous phenomena associated with flooding events initiated by natural and human induced events external to the site.

1.7. The Safety Guide presents guidelines for the analysis and quantification of flood induced effects in all the phases of the project: from the site selection phase (regional analysis, screening and ranking phases) to the definition of the design basis and from the design of measures for site protection and monitoring up to the periodic site review (see Ref. [5]).

SCOPE

1.8. This Safety Guide discusses the phenomena, both natural and human induced, that may cause floods or droughts at coastal and river sites, and gives an outline of the methods that can be used for and the critical factors involved in the evaluation of such events and of their associated effects. Possible combinations of two or more phenomena that can give rise to flooding at a site are also discussed.

1.9. The present Safety Guide discusses the hazard definition for the site and the general derivation of the design basis for the interacting effects on the nuclear power plant as a whole, to be used in a design framework or in a design assessment framework. The next step in the full determination of the design basis for a specific plant, which includes the load definition, is carried out in a design context, being intrinsically dependent on the layout and design of the plant. This additional step is therefore discussed in a Safety Guide relating to the Safety of Nuclear Power Plants: Design [6], together with the detailed loading schemes and the design procedures. Some design considerations are anticipated here in relation to site protection measures only, since they are traditionally considered part of the site evaluation process.

1.10. The installation of additional nuclear power units is under consideration for a number of nuclear power plant sites. The re-evaluation of existing sites is sensitive because of the need to reconcile an evaluated and accepted situation with a new evaluation performed by new methods on the basis of new data. This may indicate a need to upgrade the safety of the site for the older installations on the re-evaluated site. This Safety Guide does not explicitly discuss the re-evaluation of an existing nuclear power plant site, but it provides many elements that could be useful for such a re-evaluation.

1.11. This Safety Guide discusses the applicability of different methods for the evaluation of the flood hazard. Dam failures, tsunamis and other very rare events may generate a flood substantially more severe than floods due to precipitation. Generally, very few historical data are available and special techniques have to be developed. The static and dynamic effects of floods resulting from various combinations (independent and interdependent) of surface waves of differing frequency are also discussed. Consideration is also given to the effects of shoreline instabilities and erosion.

1.12. The phenomena of the lowering of water levels at coastal sites caused by offshore winds, low tides, wave effects, draw-down caused by tsunamis and drought (at the river sites also) are not discussed here as these phenomena are not expected to challenge structures and equipment but only the availability of cooling water. Although reference is made to Safety Guides [6, 7] for the relevant safety and operational aspects, the hazard evaluation may follow methods and recommendations provided in the present Safety Guide since the reference scenarios of flood and drought are often similar in nature.

1.13. Two types of method for flood evaluation for coastal and river sites are discussed in this Safety Guide: probabilistic methods and deterministic methods. Both approaches are discussed without details of the method, but with a strong emphasis on their applicability, constraints, reliability and suitability for use in meeting the requirements for site evaluation.

1.14. The potential transport of radioactive material by a flood and its dispersion in the environment is not treated in this Safety Guide. For a detailed analysis of such dispersion, see Ref. [7].

1.15. This Safety Guide does not deal with floods caused by any acts of sabotage on or off the site.

STRUCTURE

1.16. The structure corresponds to the logical sequence of the analyses required for the definition of the design basis flood[2] from the site survey stage up to the definition of the design basis and the periodic safety review on the basis of monitoring results. In particular, Section 3 deals with the preliminary investigation for site selection and Section 4 with final data collection for the site assessment up to the definition of the parameters (and probabilities, if required) for the cause of initiation of the flood (precipitation, tornadoes, earthquake and dam failures).

1.17. Sections 5 to 12 deal with the derivation of the probable maximum flood, probable maximum seiche from runoff, probable maximum storm surge and probable maximum tsunami at the site, after simulation of the effects on the site and the presentation of the possible combinations.

1.18. Section 13 deals with measures for the protection of the site from floods and flood induced events. Section 14 deals with specific mechanisms for periodic review of the flood hazard for the possible effects of modified site conditions and global warming. Section 15 deals with the monitoring of flood related initiating causes and their effects.

1.19. The annex provides examples from the experience of some States in relation to loading combinations.

---

[2] The design basis flood is the flood selected for deriving the design basis for a nuclear power plant.

2. GENERAL APPROACH TO EVALUATION OF THE FLOOD HAZARD

FLOOD SCENARIOS

2.1. The safety of nuclear power plants can be seriously affected by flooding, both for sites on rivers and for sites on the sea coast (including enclosed and semi-enclosed water bodies) or large lakes.

2.2. Floods can be associated with either ‘frequent’ or ‘rare’ events, according to the definitions provided in Refs [1, 4]. The procedures to be used for data collection and the methods to be used for hazard evaluation will depend to a large extent on the nature of the flood.

2.3. The design basis flood has to be derived from the flood hazard for the site, which is a probabilistic result derived from the analysis of all the possible flooding scenarios at the site. However, in some cases the design basis flood is evaluated via deterministic methods and no probability is attached to it. In these cases a probabilistic evaluation should always be carried out to be able to compare the contributions of different design basis scenarios to the overall plant safety (see Ref. [6]) and to evaluate the overall probability of radiological consequences of a potential plant failure.

2.4. The design basis flood is a series of parameters that maximize the challenge to plant safety as a consequence of a flood: the parameters may be associated, for example, with the maximum water level, the maximum dynamic effect on the protection or the maximum rate of increase in water level

2.5. For *coastal sites* (sea, lakes and semi-enclosed water bodies) the flood hazard is related to the most severe among the following types of flood, where applicable:

(1) The flood resulting from the probable maximum storm surge[3] (see Ref. [4] for guidance on the associated meteorological hazard);

---

[3] A storm is a violent disturbance of the atmosphere attended by wind and usually by rain, snow, hail, sleet or thunder and lightning. A storm surge is the accumulation of water at shallow depths due to wind stress and bottom friction together with the atmospheric pressure reduction that occurs in conjunction with severe storms. The probable maximum storm surge is the hypothetical storm surge generated by either the probable maximum tropical cyclone or the probable maximum extra-tropical storm.

(2) The flood resulting from the probable maximum tsunami[4] resulting from an earthquake (see Ref. [2] for guidance on the seismic hazard), and also from landslides (including landslides under the sea), undersea volcanoes and falling ice[5];
(3) The flood resulting from the probable maximum seiche[6];
(4) The flood resulting from wind and wave effects, to be considered independently or in combination with the above mentioned flood mechanisms.

2.6. A conservatively high reference water level[7] should be considered for each of these cases to allow, where applicable, for tides, sea level anomalies[8] and changes in lake levels and flood levels on rivers. Detailed recommendations on the approach to be followed are provided in Section 4.

2.7. For *river sites* the flood hazard is associated with one or more of the following scenarios:

(1) The flood resulting from off-site precipitation[9] with waters routed to the site (see Ref. [4] for guidance on the precipitation hazard);

---

[4] A tsunami is a wave train generated by impulsive disturbances of a water surface due not to meteorological but to geophysical phenomena such as submarine earthquakes, volcanic eruptions, submarine slumps, landslide or ice blocks falling into a body of water. The probable maximum tsunami is the hypothetical tsunami having that combination of characteristics which will make it the most severe, in terms of flooding, that can reasonably be expected to occur at the site.

[5] Ocean impacts may also be the cause of a tsunami. The impact of an asteroid or comet on an ocean may be a significant cause of major tsunamis that affect populations quite different from the populations affected by tsunamis caused by geological events. Such an event may be considered in the analysis of beyond design basis events.

[6] A seiche is an oscillation of an enclosed or semi-enclosed body of water in response to an atmospheric, oceanographic or seismic disturbing force. The probable maximum seiche is the hypothetical seiche which results in the most adverse flooding at the site that can reasonably be considered possible.

[7] The reference water level is a conservatively estimated reference water level used for purposes of flood evaluation, either high or low (for the evaluation of flooding or of the minimum water level, respectively), including, as appropriate, components such as the tide, river flow and surface runoff but not including increases in the water level resulting from surges, seiches, tsunamis and wind waves.

[8] A sea level anomaly is an anomalous departure of the water surface elevation from the predicted height of the astronomical tide.

[9] Flooding caused by on-site precipitation is discussed in Ref. [4].

(2) The flood resulting from snowmelt [4], seasonal floods [4] or floods relating to volcanism;
(3) The flood resulting from the failure of artificial or natural structures for water control, due to either seismic or hydrological causes or the faulty operation of these structures, identified as the probable maximum dam break;
(4) The flood resulting from the obstruction of a river channel (downstream or upstream) by landslides, ice, jams caused by logs or debris, or lava or ash from volcanic activity (this is also included in the probable maximum dam break);
(5) The flood resulting from large waves induced by volcanoes, landslides or avalanches in water basins or by waterspouts;
(6) The flood resulting from changes in a natural channel;
(7) The flood resulting from wind waves on large rivers or estuaries;
(8) The flood resulting from increasing groundwater levels, which may be caused by an earthquake (see also Refs [2, 3]).

2.8. It should be borne in mind that, in spite of the accepted terminology for the probable maximum storm surge, probable maximum tsunami, probable maximum seiche and probable maximum dam break, such events cannot always be characterized in a purely probabilistic framework. However, the terminology emphasizes that an estimate should always be made of the probability of exceedance associated with the design basis scenarios, even when they are investigated by means of deterministic approaches.

2.9. In this Safety Guide, recommendations are made for selecting the event with the worst effects on the site due to flooding, which may be different from the event with the most extreme values of a single flood parameter.

2.10. Combinations of two or more dependent events should be carefully analysed with account taken of the dependence or independence of the events. For example, on a river site exceptional spring runoff floods may cause the collapse of an ice jam resulting in higher water levels at the site and the possible obstruction of water intakes by ice floes. On a coastal site a tsunami or a storm surge may occur at the time of an exceptionally high tide. Special attention should be paid to sites on estuaries for which flood scenarios may show aspects of both coastal and river sites.

2.11. Special attention should be paid to flooding induced by rising of the groundwater level as a consequence of the influence of the sea or of a river, and also of other phenomena such as earthquakes or volcanism.

EXPECTED MAIN EFFECTS OF FLOODING ON NUCLEAR POWER PLANT SITES

2.12. The effects of flooding on a nuclear power plant site may have a major bearing on the safety of the plant and may lead to a postulated initiating event (PIE) that is to be included in the plant safety analysis. The presence of water in many areas of the plant may be a common cause of failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility of losing the external connection to the electrical power grid, the decay heat removal system and other vital systems. Details are provided in Ref. [6].

2.13. Considerable damage can also be caused to safety related structures, systems and components by the infiltration of water into internal areas of the plant, induced by high flood levels caused by the rise of the water table. Water pressure on walls and foundations may challenge their structural capacity. Deficiencies in the site drainage systems and in non-waterproof structures may also cause flooding of the site. This has happened in many cases in the past, with consequent large scale damage documented, and the possibility should be considered in the hazard evaluation and in the design of measures for site protection.

2.14. The dynamic effect of the water can be damaging to the structure and the foundations of the plant as well as the many systems and components located outside the plant. In such cases there could also be major erosion at the site boundary, which should be studied and taken into consideration.

2.15. A flood may transport ice floes in very cold weather or debris of all types which may physically damage structures, obstruct water intakes or damage the water drainage system.

2.16. Flooding may also affect the communication and transport networks around the plant site. The effects may jeopardize the implementation of safety related measures by operators and the emergency planning by making escape routes impassable and isolating the plant site in a possible emergency, with consequent difficulties in communication and supply. A flood that makes the road network around the plant impassable could also cause an emergency.

2.17. Flooding can also contribute to the dispersion of radioactive material to the environment in an accident [7]. Such an effect should be considered in the definition of the reference probability level to be used in the evaluation of the design basis flood on the basis of the flood hazard.

2.18. Other information on the causes and effects of flood induced phenomena may be found in other Safety Guides relating, respectively, to earthquakes [2], wind and snow [4], groundwater flow [3], and dispersion in air, water and groundwater [7].

METHODS FOR EVALUATION OF THE DESIGN BASIS FLOOD

2.19. Different methods are used in flood hazard evaluation according to the site evaluation phases defined in the Requirements [1]: site selection, site assessment, the pre-operational phase and the operational phase (including periodic safety review). The different aspects of flood hazard evaluation in the different phases are considered explicitly in this Safety Guide. To this end, a quality assurance programme should be established and implemented to cover items, services and processes that affect safety and that are within the scope of this Safety Guide. The quality assurance programme should be implemented to ensure that data collection, data processing, field and laboratory work, studies, evaluations and analyses and all activities that are necessary to follow the recommendations of this Safety Guide are correctly performed.

Deterministic methods

2.20. Deterministic methods[10] are based on the use of models to describe the system; these models may be empirical or based on physical relationships. For a given input or set of initial and boundary conditions, the model will generate a single value or a set of values to describe the state of the system. To obtain conservative estimates, appropriate extreme or conservative values of the input parameters should be used.

2.21. In general, deterministic methods may provide rational limits to the statistical extrapolation by means of the concept of the 'physical limit': an upper limit to the flooding level, irrespective of the probability of its occurrence. Deterministic methods may perform an important function, also

---

[10] A deterministic method is a method for which most of the parameters used and their values are mathematically definable and may be explained in terms of physical relationships.

providing a useful alternative validation of the results of the probabilistic methods.

2.22. Deterministic methods necessitate the consideration of specific features of the region and the application of engineering judgement. Where deterministic methods are applied to derive the storm generating the probable maximum storm surge, this storm should be used as input to the surge and wave models for the evaluation of the design basis.

Probabilistic methods

2.23. Probabilistic methods are based on time series[11] analysis and synthesis. They combine deterministic and statistical analysis, and they synthesize a time (or space) series of stochastic variables[12] and the effects of a limited number of data. It is assumed that the series represents both definable causes and an unknown number of stochastic causes, and that the stochastic causes are reasonably independent. With these methods, jumps, trends and outliers of the data set can be adequately taken into account. It is emphasized that the data used in probabilistic evaluations are based on actual measurements or variables. As with deterministic methods, probabilistic methods should be used in conjunction with engineering judgement; when it is feasible, they should be checked by the use in parallel of a simplified deterministic analysis.

Use of deterministic and probabilistic methods

2.24. In general, deterministic and probabilistic methods should be seen not as competitive but rather as complementary. For example, if a surge is generated by a tropical cyclone, the evaluation is usually carried out by deterministic methods with account taken of the more symmetrical characteristics of the generating storm. Surges generated by extra-tropical storms have been evaluated mainly by stochastic methods since such storms are usually very

---

[11] A time series in this context is a chronological tabulation of data measured continuously or at stated time intervals (e.g. mean daily flow, maximum annual flood and daily water level at 08:00).

[12] A stochastic variable (as used in hydrology) is a variable whose value is basically of a probabilistic nature, but that may include a non-random dependence on time (or space). In a stochastic time series, one term in the series may be significantly related to neighbouring terms, and this possibility is taken into account in the analysis and synthesis of the series.

extensive, asymmetrical and difficult to model. Deterministic methods should be used as a complementary method for evaluating these surges.

2.25. In general, the flood hazard should be compared critically with recorded and historical data and the design basis flood should be set at a value not less than a recorded occurrence plus a substantial margin that should be related to the length of the period over which measurements were made and the local situation. This should only be done provided that there has been no significant change in the basin either upstream or downstream of the site.

2.26. A dam failure or tsunami, where applicable, may generate a flood substantially more severe than any due to natural meteorological phenomena. For these cases the site specific methods outlined in the subsections should be used to estimate the order of magnitude of the flood hazard.

2.27. In both deterministic and probabilistic cases, a reference probability of exceedance value for the initiating event and for the site flood should be defined and attached to the design basis flood. The definition of such a value should be closely connected with the conditional probability that such an event (or accidental sequence) would have serious radiological consequences[13].

2.28. In all cases the margin of uncertainty in the result should be determined. This may be done by testing the degree to which predictions are affected by varying the values of relevant parameters and by evaluating the effect of the overall level of uncertainty in these parameters. Different methods should be used to check the conservativeness of the chosen safety level.

---

[13] The reference probability of exceedance value for the initiating event and for the site flood is defined in different ways in different States. The probability of occurrence of an event generating the design basis flood can be taken to be one or more orders of magnitude greater than the probability associated with the design basis flood, to provide the necessary target for probabilistic methods and reasonable equivalent thresholds for deterministic methods. Moreover, the selection of the probability level for the design basis flood should guarantee that a sufficient margin of safety remains to protect the plant against serious radiological consequences. For example, if the probabilistic limit for a serious radiological accident is 1×10^{-7}/a, then the probability of occurrence of a design basis flood may be 1×10^{-4}/a provided that in the event of flooding the margin of safety for (i.e. conditional probability of) a serious radiological accident remains smaller than 1×10^{-3}/a.

2.29. Both deterministic and probabilistic methods suffer in general from constraints that limit their applicability and necessitate an evaluation of their reliability. For example, with deterministic methods it is not possible to express the level of safety quantitatively, and with probabilistic methods there is a lack of confidence in the results of the extrapolation to very low probabilities of exceedance. In addition, the use of deterministic methods requires data for the region which, in some parts of the world, may not be available. Similarly, the use of probabilistic methods requires measurements which may not be available. The quality and extent of available historical series of data should be considered as reference criteria in the choice of the type of method.

3. PRELIMINARY INVESTIGATIONS

GENERAL

3.1. The potential for flooding is one of the site characteristics that should be evaluated during both the regional analysis of the site selection phase for a nuclear power plant development project and the site assessment phase, according to the general procedures set out in Ref. [1].

3.2. As the most suitable protection against flooding, the plant should be constructed at a level where it will not be affected by floods. The preliminary evaluation of the flood level is therefore extremely important and should be given due attention in selecting a site.

3.3. At the stage of site selection, it may be evident in certain cases that there is no potential for flooding, because of location or elevation for example. In this case the preliminary assessment should be sufficiently well documented to demonstrate either that the plant would not be affected by any potential flooding or that the potential for flooding is insignificant and has a negligible affect on safety.

3.4. It is not usually practicable to make detailed flood analyses at the site selection stage, and empirical and approximate methods are generally used to estimate roughly the extreme flood. The choice of method will depend on the data available and the characteristics of the region. The results of the evaluation should be compared critically with any data measured or otherwise recorded.

3.5. The reference sites discussed in this Safety Guide pertain to two main categories:

(1) Sites vulnerable to coastal flooding are those located in open coastal regions, and on semi-enclosed bodies of water and enclosed bodies of water of such an extent that the hydrological response cannot be compared with that of a small lake. Open coastal regions are those areas of land directly exposed to and having a shore on a major body of water. Semi-enclosed bodies of water are lagoons, river estuaries, gulfs, fjords and rias. Enclosed bodies of water are lakes and reservoirs.
(2) Sites vulnerable to river flooding are those located on river coastal regions or in general in river basins.

3.6. The different natures of flood generating phenomena should be considered in data collection and processing. Floods exhibit major differences in their characters and causes associated with their nature:

(1) *Frequent phenomena*. For frequent phenomena, flood related variables such as water level, amount of precipitation and wind speed characterize the marine, meteorological or climatological environment. The extreme values of these variables can be derived by statistical analysis of routine measurements over a network of fixed stations by international, national, local or private oceanographic, hydrographic or meteorological services.
(2) *Rare phenomena.* Rare phenomena are phenomena such as tsunamis or dam breaks which occur infrequently. At any particular station, the instruments used for routinely measuring variables would rarely have registered characteristics of these phenomena, and generally therefore modelling is used extensively and comparisons with sites elsewhere are made. The intensity values of rare phenomena may be expressed in terms of either a qualitative characteristic such as damage or a quantitative physical parameter.

COASTAL SITES

3.7. For a regional analysis where the region includes a coast, a preliminary study of coastal floods should be performed. At the preliminary phase of site selection the most important flood causing events, in particular surges, tsunamis, seiches and waves, should be determined, together with the reference level components. If the potential for coastal floods is significant and it is decided to consider coastal floods in the regional analysis, then approximate methods such as those mentioned below should be used to identify areas affected by surges, seiches and tsunamis and the appropriate components of the reference water levels:

(a) The parts of the coast most frequently subjected to surges, tsunamis and severe wind waves should be determined from maps prepared for land use planning and flood emergencies. Although the return time of the events considered for drawing these maps is usually short (e.g. 30–50 years), they can nevertheless be very useful in a preliminary screening.
(b) Aerial photographs and satellite imagery may also be helpful in determining areas subject to flooding.
(c) If detailed determinations of the probable maximum storm surge or probable maximum tsunami have been made for the region, envelope curves should be prepared for the part of the coast being studied and the magnitude of the results should be evaluated, with account taken of the effects of waves and tides. It may be useful to plot extreme surges or tsunamis of known mean return time (e.g. 100, 50 or 20 years) derived from historical data on the same graph together with estimated values of probable maximum storm surge or probable maximum tsunami.

3.8. For site assessment at the feasibility and verification stages (i.e. the evaluation of the suitability of a site to host a plant), first the large scale and long term weather pattern of the area should be established, then a preliminary evaluation of the important flood causing events for the proposed site should be undertaken.

3.9. A more detailed study than that conducted in the regional survey of the meteorological extremes for the region should be carried out. Recommendations and guidance on methods and parameters are provided in Ref. [4].

3.10. The potential for storm surges at a site should be assessed on the basis of meteorological and hydrological information. If there is found to be a potential for storm surges, a preliminary estimate of the storm surges at the site should be made. Case studies of actual severe storms in the region should be used to identify the following characteristics of the critical storm that would produce surges at the site with a sufficiently low probability of being exceeded (see also Ref. [4]):

- minimum central pressure and associated peripheral pressure,
- maximum sustained wind speed and its direction,
- wind fetch[14],
- duration of storm and associated winds,
- direction and speed of movement of the storm,
- the storm track and particularly the point at which the storm track is closest to or crosses the coast.

3.11. A preliminary estimate of the height of the probable maximum storm surge should then be made by using the values of parameters representing the characteristics listed as inputs to empirical relationships. Whenever possible, these results should be compared with historical records of storm surges to check the suitability of the method used. A method that results in a calculated extreme event that is lower in magnitude than any event that was recorded is unacceptable.

3.12. Information on tsunamis should be collected if the site is located in a region that is affected by tsunamis. Although it is estimated that 80% of all tsunamis occur in the Pacific Ocean, destructive events of this type also occur in the Atlantic Ocean, the Indian Ocean, the Caribbean Sea, the Mediterranean Sea and their adjoining bodies of water. Catalogues of records of tsunamis should be carefully analysed.

3.13. The potential for offshore seismic or volcanic activity, and the vulnerability of the site to tsunamis emanating from both local and distant areas should be investigated even though no such waves from these areas may have been recorded over historical time.

3.14. Probabilistic or simplified deterministic methods for evaluating tsunamis are appropriate for use at this stage. With information gained from the list of known and suspected tsunamis, the procedure includes the review of all hydrographs for a specific gauge station in the region of the site to determine whether there is evidence of tsunami activity.

3.15. For part of the list of known and suspected tsunamis, arrival times and the height of the maximum tsunami wave, from trough to crest, with the tide

---

[14] The fetch is the extent of sea water over which the wind under consideration blows, measured in the direction of the wind.

subtracted, can be extracted from the records. A plot of the maximum tsunami waves against the mean return time should be used as a basis for predicting the extreme tsunami wave to be expected at the gauge station. The correlation between the tsunami response at the gauge station and that at the site should be investigated by means of a study of the coastal features. Since the maximum tsunami heights on the hydrographs may differ significantly from observed runups[15] at adjacent shore locations, comparisons between known flood levels at the sites and those at the gauge stations should be carried out whenever possible.

3.16. Preliminary estimates should be made of the height and range of the extreme wave for a coastal site. They should be based on collected historical data for maximum wave heights along the coast, modified as necessary by the use of data on the bathymetry of the seabed facing the site. If historical wave data are not available, wave parameters should be estimated on the basis of wind and fetch data by using wave forecasting curves.

3.17. A preliminary estimate of a conservative reference water level to be considered jointly with the characteristics of the surge, seiche, tsunami or wave should be made at this stage. For coastal sites the astronomical tide height is an important component of the reference water level.

RIVER SITES

3.18. For the regional analysis of river floods and the systematic survey of large areas, the following approximate methods should be used:

(a) If detailed determinations of the flood hazard have previously been made in the region, envelope curves should be prepared for similar basins in the same region and the magnitude of the flood hazard should be estimated. The drainage area should be plotted against the peak flow, or more elaborate procedures based on the envelope of available data may be preferred. It may be useful to plot curves of floods of known mean return time (e.g. 100, 50 or 20 years) and flood hazard curves on the same graph.

---

[15] The runup is the rush of water up a beach or structure on the breaking of a wave. The height of the runup is the vertical height above the still water level that the rush of water reaches.

(b) For the rapid estimation of flood hazard, a multiple regression analysis should be made of the drainage area, the rainfall index, soil conditions and urbanization.
(c) Envelope curves of historical flood peaks in the region versus the drainage area should be produced for estimating the flood hazard.
(d) For some areas, studies of the relationship between floods of known mean return time and the flood hazard have been made or if not they should be made. Such information may provide rough approximations of the flood hazard required.
(e) By using aerial photographs and satellite images, areas that are subject to flood hazards should be identified and approximate checks should be performed of the relationship between the flow and level of the flood and the extent of the flooded areas.

3.19. The following approximate methods should be used for site assessment purposes, according to the availability of data:

(a) Empirical curves extrapolated to low probabilities should be used for site screening purposes in cases for which flow records over 30 or more years are available, as a first indication of the level of protection necessary. When an approximate value of the flood flow has been obtained, the peak water level should be estimated by means of Manning type formulas on the basis of the average river channel bottom slope, the river cross-sectional areas and conservative friction factors.
(b) Empirical formulas should be used for drainage basins of a few hundred hectares in area in which runoff characteristics are not influenced by the presence and operation of water control structures.
(c) A simple and approximate procedure that should be used, if necessary, for evaluating the effects of dam failures is to assume that all relevant upstream dams fail at such times as to produce the maximum potential flood. Constructions and obstructions downstream from the dam and from the site should be taken into consideration.
(d) Frequency curves and relationships between flows and levels should be extrapolated and historical data should be used to check and possibly to improve on the results.

STABILITY OF THE SHORELINE AND RIVERBANK

3.20. A preliminary investigation should be undertaken to determine whether there is a potential for instability of the shoreline or riverbank since erosion over the lifetime of the nuclear power plant could affect items important to safety. Erosion maps and tidal current maps, aerial photographs and satellite images are very useful and should be used where possible for studying erosion over large areas. Information on the importance of erosion in historical times should be used at this stage.

EFFECTS OF ICE

3.21. For sites in the higher latitudes, information on regional ice conditions should be considered at this preliminary stage.

OTHER POTENTIAL CAUSES OF FLOODING

3.22. Preliminary historical data should be collected at this stage about landslides, avalanches, volcanoes and the modification of the river channel.

4. DATA COLLECTION AND SITE CONFIRMATION

GENERAL

4.1. After the site selection phase, if it is established that there is a potential for flooding or for serious erosion at a site, a detailed study should be undertaken to detect the reference mechanism for site flooding and, therefore, to define the relevant design basis flood for the plant. A similar study should be carried out within the framework of a safety assessment of the plant. In this latter option, the data from the site monitoring system which has been in operation since the preliminary phase of site evaluation should have the highest priority.

4.2. The data should be presented on maps of the appropriate scale, on graphs or in tables. In some cases, where the existing network for collecting meteorological and hydrological data in the basin is inadequate, supplementary observation stations should be installed and operated. Although the time available for collecting supplementary data is usually relatively short, the information that can thus be obtained may be important.

DATA RELEVANT TO COASTAL SITES

4.3. Hydrological data to be collected include the following data:

- The locations and hydrological characteristics of all relevant bodies of water[16] such as streams, rivers, natural and artificial lakes and groundwater;
- The description of the site, including topographical maps showing natural and artificial drainage features and any proposed changes;
- Tides and daily water levels (hydrographs) of the bodies of water in the region;
- The flood history in the region, including historical flood marks and information such as flood hydrographs, their dates of occurrence, and peak flows and levels.

4.4. The oceanographic and hydrographic data to be collected, if relevant for the region, include the following data:

- The bathymetry of the water bodies, in particular the detailed bathymetry of the near shore area fronting the plant site;
- Wave and swell observations for both normal and storm conditions;
- Surges and seiches, including peak levels, hydrographs and their respective dates of occurrence;
- Tides, estuaries and sea level anomalies;
- Tsunami runups and draw-downs, including peak elevations, hydrographs and dates of occurrence;
- Ice in seas and estuaries, including types, coverage, thickness and duration;
- Near shore currents induced by tides and wind, sand movement and bathymetry (this information is necessary if shoreline erosion is critical to safety);
- Long term and short term erosion data (from sources such as old surveys, maps, aerial photographs and satellite imagery).

---

[16] Relevant bodies of water are all streams, rivers, artificial or natural lakes, ravines, marshes, drainage systems and sewerage systems that may produce or affect flooding on or adjacent to the nuclear power plant site. Bodies of water that are outside the watershed in which the plant is located, but that may, by overflowing the watershed divide, produce or affect flooding of the plant site, are also considered relevant bodies of water.

4.5. If no reliable, detailed topographic and bathymetric maps are available for the immediate area around the plant site, surveys should be performed to prepare such maps. Normally these maps include the shoreline area fronting the plant and a detailed bathymetry from the shoreline out to an adequate depth (usually 30–50 m). These bathymetric and topographic maps are matched to one another at the shoreline. They may also be needed for other planning purposes that are outside the scope of this Safety Guide such as the analysis of offshore discharges. Depth contours on the bathymetric maps are usually at intervals of approximately 1 m from the shoreline to about 6 m water depth and at intervals of approximately 3 m from 6 m depth out to the 30–50 m contours. The intervals are approximate and may vary depending on site conditions. Contours below 30–50 m water depth should be available from nautical navigation charts; otherwise an appropriate survey should be conducted.

4.6. For bathymetric surveys a base level should be established. For a fixed base level, if not already available, a system of benchmarks should be arrayed and correlated with the national system of benchmarks.

4.7. Historical data on levels of seiche oscillations of the water body near the site should be collected and analysed. They can be used for checking the results of a deterministic estimate of the severity of seiches or as a basis for a stochastic evaluation.

4.8. The absence of a potential for seiches deriving from landslides or seismic excitation cannot be established solely on the basis of historical data because these phenomena may not have occurred over the period of historical record. The stability of the slopes of the basin perimeter and the potential for seismic excitation causing seiches should therefore be investigated.

4.9. A reference water level should be established for each flooding event or for each combination of flooding events. Some of the phenomena that should be studied for establishing these levels are:

- the astronomical tide,
- the sea level anomaly,
- the changes in levels in enclosed bodies of water such as lakes and reservoirs;
- the changes in levels due to the river flow,
- the possible changes in levels in the future due to major changes expected in the world climate.

Astronomical tides

4.10. The tidal range can differ greatly from place to place. Harmonic analysis, in which the tidal oscillations are separated into harmonic components, is frequently used in the calculation of tides. Harmonic constants for the prediction of tides at gauge stations near the selected site may be obtained from the national authorities.

4.11. In computing the probable maximum storm surge on the open coast, a high tide with a sufficiently low probability of being exceeded should be considered to occur coincidentally with the probable maximum flooding event. The value of the probability is selected with account taken of the contributions of the tide to the water level for different values of probability. Values for the high tides to be assumed coincidentally with the various flood events are presented in the Annex.

4.12. Special consideration should be given to the changes in level and to tidal bores, which occur in some estuaries when the tide is changing.

Sea level anomalies

4.13. Sea level anomalies are departures of the water surface elevation from those of predicted astronomical tides. Sea level anomalies should be estimated by comparing long term recorded astronomical tides with predicted astronomical tides or by means of an analysis of changes in the mean sea level.

4.14. In determining the probable maximum storm surge, a sea level anomaly should be taken into consideration if the selected representative high tide is based on predicted tide levels only. If the selected representative high tide is based on recorded tides, a sea level anomaly should be taken into account only when systematic changes in tide levels are found. If long term recorded tidal data show average high levels or average low levels that are consistently increasing or decreasing in comparison with those for the predicted astronomical tides, the changes in the tide should be considered to be the sea level anomaly. In this case a prediction for the change in tide for the lifetime of the nuclear power plant should be added to the selected representative high tide for use in determining the design values.

Level in enclosed bodies of water

4.15. The reference water level in an enclosed body of water which is not subject to human control should be taken as the mean value of all data on the water level for a certain time period. Surge and seiche effects cause changes in the transient water level only and do not significantly change the mean water level. The reference water level upon which the computed probable maximum storm surge or probable maximum seiche is superimposed should be selected so that the probability of its being exceeded over the lifetime of the plant is sufficiently low[17].

DATA RELEVANT TO RIVER SITES

4.16. For a statistical analysis of a time series suitable for a site assessment, data over a minimum of 50 years should be collected. Hydrological data to be collected should include data on the following:

- The locations and hydrological characteristics of all relevant bodies of water in the region;
- A description of the site, including topographical maps showing actual drainage features and any proposed changes;
- The locations and description of existing and proposed water control structures, both upstream and downstream of the site, that may influence site conditions;
- The history of floods in the region, including historical flood marks and information such as flood hydrographs, their dates of occurrence, and peak flows and levels;
- The river channel (hydraulic and geometric data);
- Records of daily flows and maximum annual floods as well as historical flood marks, if available, for the period of record at the gauges nearest to the site and at all relevant gauges in the hydrologically homogeneous regions[18] that include the basins of the relevant water bodies.

---

[17] States have different criteria for the water level, such as:

- The 10% exceedance high tide (i.e. the high tide that is equalled or exceeded by 10% of the maximum monthly astronomical tides over a continuous 21 year period);
- The mean annual spring tide;
- The highest astronomical tide in a 19 year period.

[18] A hydrologically homogeneous region is a region for which a hydrological model can be used to transfer hydrological data using the same parameters, systematically varied, as functions of definable space variable characteristics of the region.

4.17. When sites are located along semi-enclosed bodies of water, such as river estuaries, the reference water level may depend on astronomical tides in combination with the river flow. In regions where extreme floods arise mainly from oceanographic causes, it is necessary only to choose an appropriate value for the river flow (not to be exceeded in tens of years); this should be considered in conjunction with the appropriate combination of probable maximum surge, tsunami, wind wave and tide to derive the design basis flood. In other cases, where the river flood is more important, the solution adopted should be appropriate to the particular case[19].

METEOROLOGICAL DATA

4.18. Procedures for data collection and processing are described in Ref. [4].

SEISMIC AND GEOLOGICAL DATA RELEVANT TO COASTAL SITES

4.19. Seismic and geological data to be collected, if there is a potential for tsunamis, include the following data:

- All the relevant historical data on tsunamis, in particular tsunamis at the site, at other coastal locations with a topography and bathymetry similar to the site under consideration and at other coastal locations where no significant amplification of tsunamis can be expected;
- Seismic and geological data for use in determining the source characteristics of the most severe potential tsunami generator, both local and distant;
- Topography and coastal bathymetry out to the depth necessary for an adequate evaluation, which may be at the edge of the continental shelf;
- Undersea and subaqueous landslides and volcanic activity;
- Sediment types and erodibility characteristics of the sea bottom near the cooling water structure and the plant facility.

---

[19] Examples of these cases are:
- A site in the transition zone between an oceanic regime and a river regime, where extreme water levels can be caused by both oceanographic phenomena and river flow.
- A site where the drainage area of the river is in a tropical cyclone area such that the probable maximum tropical cyclone not only causes a surge but can also cause a flood on the river. This offers the possibility of a coincidence of both the design basis flood due to precipitation and the probable maximum storm surge on the coast.

SITE MORPHOLOGY DATA

Description of the coast (coastal sites)

4.20. In addition to the oceanographic, hydrographic, topographic, hydrological, meteorological, seismic and geological data discussed above, natural and human induced characteristics of the site's coastal topography should be described in the detail necessary for an analysis of coastal floods.

4.21. The bodies of water in the area that may influence floods at the site should be described; these may include lakes, estuaries, rivers and bays. For lakes the description includes the average level and the normal range of levels and, in the case of ocean or estuary sites, the normal tidal ranges. The data to be collected, most of which should be conveniently presented in the form of maps and tables, include in particular:

- A detailed contour map of the area in the vicinity of the site;
- A smaller scale contour map to demonstrate the overall exposure and the relationship of the site to sea or ocean;
- The bathymetry of offshore areas (more detailed in the inshore shallower water area);
- Sediment types and erodibility characteristics of both shoreline and near shore bottom areas;
- Land cover;
- Natural coastal or offshore features or obstructions, and their locations and descriptions, including anticipated modifications;
- Human made coastal or offshore structures (existing or planned), their locations and descriptions, and any known or anticipated effects on flooding.

Description of the drainage basin (river sites)

4.22. Flood analysis requires a thorough knowledge of the drainage basin. The basin characteristics have a significant influence on the peak and shape of the hydrograph, on the lag time between precipitation or snow melt and the occurrence of flooding, and on the sedimentation and the erosion patterns that can occur during floods as well as in other periods. All this information should be carefully collected and evaluated. A knowledge of these characteristics helps greatly in understanding the origin and the pattern of development of floods produced by factors other than runoff from rain and/or snow melt, such as ice effects, landslides and changes in basins and channels due to natural and artificial causes. Human induced changes in the basin may produce deviations from steady state behaviour in the time series of flood data. Information on both natural and human induced characteristics of the basin should therefore be collected.

4.23. Information should be collected on the basin's natural characteristics, in addition to the hydrological and meteorological data, including as appropriate:

- The boundaries of the watershed;
- The detailed topography;
- Geology and hydrogeology;
- The identification of landslide prone areas;
- Seismic and volcanic characteristics;
- Soil characteristics, in particular those relating to infiltration and erodibility;
- The land cover, in particular vegetation types, lakes, marshes and glaciers, areas prone to glacially induced surges, areas of perennial snow and areas prone to avalanches;
- Changes in vegetation cover and forest cover, and grass fires and forest fires (historical data);
- Drainage networks and hydromorphological characteristics of the channel, such as the slope, width and depth of the main channel and the flood plain, and the roughness and bed sediment characteristics of channels of various orders;
- Channel changes over historical time (historical data).

4.24. Most of the above information should be conveniently presented in the form of maps and tables. The scale of the maps should be selected to suit the size of the basin and the accuracy of the available information. In using information on the basin in the analysis, care should be taken that the use of averaged (lumped) indexes does not degrade the significance of the information.

4.25. Human interference with the hydrological characteristics stems primarily from two types of activity: (a) changes in land use; (b) modification of existing channels and valleys, for example by constructing new channels. While the effects of the second are usually obvious, the first may also be important and, in all cases, should be given careful consideration. Information should be collected on relevant past and probable future human activities, including:

(a) Changes in land use in the river basin, especially changes in:
- farmed areas and agricultural practices;
- logging areas and practices (deforestation);
- urbanized areas, population density, storm drainage practices;
- transport networks and characteristics;
- mining and quarrying activities and related deposits.

(b) Changes in channels and valleys associated with structures of the following types:
- dams and reservoirs;
- weirs and locks;
- dykes and other flood protection structures along rivers;
- diversions into or out of the basin;
- flood ways;
- channel improvements and modifications;
- bridges and transport embankments.

4.26. For the structures mentioned in subparagraph (b), information on the following should be provided, as appropriate:

- Dates of construction, commissioning and starting operation;
- Responsibility for administrative and operational control;
- The nature and type of the main structures and significant appurtenances;
- Storage characteristics, data on flood design, safety factors considered in the evaluation of the maximum, normal and average pool elevation and storage;
- Flood control and arrangements for emergency operation;
- Hydrographs for the design in-flow;
- Data on seismic design;
- The size and location of protected areas;
- The effects on water flow, ice, sediment and debris;
- The effects on river aggradation or degradation[20].

---

[20] Aggradation is a rise in the level of a river channel or flood plain. Degradation is a lowering of the level of a river channel or flood plain. Both aggradation and degradation may have various dynamic causes.

5. FLOODING BY STORM SURGES

GENERAL

5.1. In open coastal areas, the rise in water level due to a surge is usually represented by a single peak surge generated by a wind storm. On top of this, the effect of waves should be determined. In an enclosed or semi-enclosed body of water such as a lake or harbour a storm can cause the oscillation of the water surface which can result in a multipeak surge hydrograph.

5.2. Surges are generated by storms or cyclones [4].[21] The effect of concern is the water wave: the maximum surge from a cyclone at a site usually occurs when the path of the cyclone is to the left of the site in the northern hemisphere (travelling from sea to land) and to the right of the site in the southern hemisphere. The location of the maximum surge on the coast may not coincide with the location of the occurrence of the maximum wave height. The fetch used for the maximum wave conditions may be different from that used for the maximum surge conditions. Various combinations of the parameters defining the cyclone should therefore be used as inputs to the evaluation of the surge to determine those critical combinations of parameters that result in the most severe flood.

5.3. Extra-tropical storms are migratory frontal cyclones that occur in the middle and high latitudes. Such storms produce their highest winds in the cooler season of the year because they are energized mainly by the temperature difference between air masses, which is at its most pronounced in this season.

5.4. For sites on rivers or estuaries that flow into large bodies of water, the computed probable maximum storm surge will require empirical or mathematical routing upstream of the point of interest. Sites on large enclosed bodies of water should be analysed for surges by the use of one or two dimensional surge models.

---

[21] In Ref. [6], cyclonic phenomena are grouped into extended pressure systems and detailed descriptions of their characteristics are provided.

DETERMINISTIC EVALUATION OF PROBABLE MAXIMUM STORM SURGE

5.5. To derive the probable maximum storm surge by the deterministic method, a set of maximized hypothetical storms should be constructed as explained in Ref. [4], moved to the location critical for a surge at the site and then used as input for an appropriate surge model. The application of a deterministic method is not a unique process but is a combination of procedures of transposition, maximization and estimation in which the hydrologist and the meteorologist should apply their expert judgement. This procedure is readily applicable to tropical cyclones but may present some difficulties in its application to extra-tropical storms. The procedure should include the selection of the probable maximum storm to be used for surge evaluation and an evaluation of surges for open coastal regions as well as for semi-enclosed and enclosed bodies of water.

STOCHASTIC EVALUATION OF PROBABLE MAXIMUM STORM SURGE

5.6. The stochastic method should be applied to the evaluation of the probable maximum storm surge if reliable surge data (for the difference between the tide level and the final water level) are available that cover a sufficiently long period of time and for an adequate number of gauge stations in the region. The surge data should be available as still water levels[22], excluding the influence of high frequency waves and astronomical tides. This is normally the case when instrumental surge data for a certain region are available. The associated wave action should be evaluated as a separate issue.

5.7. Time series from several locations should be correlated, thus providing a basis for developing a synthetic time series that is valid over a longer interval than the time span of the local observations. The use of time series from other representative hydrometric stations will broaden the basis of the analysis and make it more reliable.

5.8. By working with actual surge levels as basic parameters, the different factors relating to the intensity, path and duration of storms are implicitly taken

---

[22] The still water level is the elevation that the surface of the water would assume if all short period wave actions were absent.

into account if the records cover sufficiently long periods of time. This approach has advantages and should be applied to the maximum possible extent, especially in regions subject to extra-tropical storms, since these storms can be very extensive and complex and they are therefore difficult to model in a form that will yield an appropriate input for the deterministic method.

5.9. Stochastic analyses do not usually give adequate information about the physical validity of the results obtained. For this reason a simplified deterministic study should be carried out to check the results of a stochastic analysis, and a physical model appropriate for the region should be used. Such a check should consist of two steps:

- The validation of the simplified deterministic model by using actual storm parameters as input to the model and by comparing the results with recorded measurements of the surges that have occurred;
- The examination of the appropriate probability, severity and physical reality of those storm parameters which, when used in the deterministic model, give the same surge level as is derived from the stochastic analysis.

PROBABLE MAXIMUM STORMS

5.10. The storm generating the probable maximum storm surge, depending on the location of the site and the characteristics of the region, can be the probable maximum tropical cyclone[23] or the probable maximum extra-tropical storm[24]. For each site the generating storm for the probable maximum storm surge

---

[23] The probable maximum tropical cyclone is the hypothetical tropical cyclone. It is characterized as a rapidly revolving storm having that combination of characteristics that will make it the most severe, in terms of flooding, that can reasonably be expected to occur in the region, and which approaches the point under study along the critical path and at a rate of movement that will result in the most adverse flooding.

[24] The probable maximum extra-tropical storm is the hypothetical extra-tropical storm (often termed a 'depression' or 'low pressure area' and generated in mid-latitudes or high latitudes of more than about 25°N or 25°S). It has the most severe combination of meteorological storm parameters in terms of flooding that is considered reasonably possible in the region, and which approaches the point under study along the critical path and at a rate of movement that will result in the most adverse flooding.

should be selected on the basis of the information provided in Ref. [4]. In computing the probable maximum storm surge, a reference water level such as the high tide or high lake level, of a sufficiently low probability of being exceeded, should be assumed to occur coincidentally with the storm surge. Considerations in relation to combined event probabilities are provided below.

5.11. The analysis consists in selecting those appropriate storm parameters and other relevant parameters (e.g. maximum wind velocity, atmospheric pressure differential, bottom friction and wind stress coefficients) to be used as inputs to a one or two dimensional storm surge model which maximizes the flooding potential. All parameters should be conservatively evaluated and adequately substantiated.

5.12. The storm surge analysis gives the following as outputs:

- Over-water wind field and pressure gradients for the initial position of each storm and for specified later times.
- Summary of storm surge calculations, including the total increase in water depth at each specified traverse depth, starting in 'deep water'[25] and continuing to shore at the initial time and at specified later times.
- Summary tables and plots of the total storm surge hydrographs for specified locations.

Open coastal regions

5.13. An appropriate validated model for calculating the probable maximum storm surge should be selected. Experience has shown that for tropical cyclones a one dimensional model may be appropriate for open coastal sites. However, for extra-tropical storms and for tropical cyclones, if the configuration of the coast or the structure of the wind field is very irregular, a one dimensional model will be inadequate, and in this case a two dimensional model should be used that has already been accepted for this purpose or has been demonstrated to be conservative. The meteorological variables characterizing such a storm are: the wind field pattern, the pressure gradient, and the track and forward speed of the storm centre. The outcome of the meteorological analysis is an

---

[25] 'Deep water' is water of a depth greater than $L/2$, where L is the wavelength of the surface wave under consideration.

extreme wind field and pressure gradient which should then be moved along various tracks with an optimum forward speed for surge generation to determine the most extreme surge for a particular location.

5.14. It is possible that the cyclone or extra-tropical storm generating the peak water level for the probable maximum storm surge may not represent the critical conditions for design. Other cyclones or storms may generate lower peak surges but may cause high water levels of longer duration, or may produce higher wind speeds and waves. The wave activity associated with these cyclones or storms could conceivably produce higher design water levels. Also, for sites located within a bay, cyclones or storms that would generate peak surges which are lower but of longer duration on an open coast could generate higher peak surges and more severe wave conditions within the bay, resulting in higher design water levels. Hence cyclones or storms other than those generating the peak open coast surge but that could produce such effects as those just described should be considered.

Semi-enclosed bodies of water

5.15. For semi-enclosed bodies of water the probable maximum storm surge should be derived by using validated one or two dimensional mathematical models. The appropriate combination of the parameters that produces the most severe surge at the site should be carefully selected. For analysing storm surges in these bodies of water, the open coast surge is usually evaluated first and then it is routed through the entrance and up the bay or river to the site. The combination of parameters generating the highest open coast surge does not necessarily generate the highest surge at a site located in a bay or estuary; however, there exists an optimized set of parameters, particularly the storm direction and translational speed as it travels up the bay or river, that will generate the maximum surge at the site. For evaluating the water movement in a semi-enclosed basin, a transient one dimensional model may be appropriate to compute resonance effects for a narrow body of water with a single entrance, whereas a two dimensional transient analysis is necessary for water bodies of other shapes. In calculating surges in a semi-enclosed body of water, the wind waves, the reference level including astronomical tides, sea level anomalies, and the appropriate bottom friction and wind stress coefficients should be conservatively selected or evaluated.

5.16. No separate computation is necessary for the open coast surge and routed surge if the area used in the two dimensional model is large enough to cover the entire wind field, so that the water level rise at the open boundary of the model is negligible. Moreover, for sites located in bays with low beach berms and low marshes, overtopping of the beach berms with flooding is possible and open coast surges with lower than maximum peaks but longer duration may generate the highest surge elevations at such sites. This possibility and the erosion of beach berms and bay entrances, which might worsen flood conditions, should be taken into consideration.

5.17. The results of the surge analysis for a semi-enclosed body of water should include the calculated time histories of the associated open coast surges, discharges of water through the entrance, surge profiles up the bay or river, contributions of set-up due to cross winds and, if applicable, contributions due to runoff and river flow.

Enclosed bodies of water

5.18. For enclosed bodies of water the probable maximum storm surge should be derived by using validated one or two dimensional mathematical models. The critical portion of the wind field, after being adjusted for any overland effects, is used as input for this analysis. The selection of coefficients and boundary conditions should be based on conservative assumptions. When one dimensional models are used, the transverse or crosswind set-up or a transverse seiche component is calculated separately and added to the longitudinal wind set-up. If the water body is sensitive to resonance, the transient responses should also be considered separately in a one dimensional model. If the water body is considered to be relatively insensitive to resonance, an analysis should be performed to substantiate this. The two dimensional transient mathematical models automatically take into account the transverse components and resonance effects. Components of the probable maximum still water levels are the longitudinal wind set-up, the transverse or cross-wind set-up and the reference water level.

5.19. The reference water level upon which the computed surge or seiche is superimposed should be selected to have a sufficiently low probability of being exceeded. Usually the 100 year recurrence monthly average high water is adopted or, if the water level is controlled, the maximum controlled water level is used. In determining the 100 year high water level, the maximum values of the 12 monthly averages in each year for the entire period of record are obtained and these yearly maximum values are then used for the frequency analysis.

6. WAVES

GENERAL

6.1. Wind generated water waves (surface gravity waves) should be taken into consideration in the flood analysis for coastal sites. The calculations of extreme events (such as surges, seiches or tsunamis) and the associated wind waves should be performed together since the results are non-linear and it is not appropriate to evaluate the partial effects separately and then add them to obtain the maximum flood level.

6.2. To determine the wave effects, first the generating wind field should be selected [4]. The deep water, transition water[26] and shallow water waves produced by this wind field should then be evaluated. Finally the near shore wave spectrum and its maximum values affecting each structure important to safety should be established. Spectra of wave heights and periods will be generated by the wind; the maximum of both the wave height and the period will vary, depending on the wind's speed, duration and direction and the fetch over which it blows and, in shallow water[27], on the water depth. These parameters are constantly changing during the movement of the storm. In determining wave effects the following aspects should be studied:

- the wind field generating the waves;
- the generation of offshore waves;
- the transformation of offshore waves;
- the near-shore wave spectrum;
- the increase in the near-shore water level generated by waves;
- the set-up, swell and local storm effects.

WIND FIELD

6.3. To evaluate waves, first the wind field generating the waves should be selected. If the wave is to be considered jointly with a surge, a type of storm

---

[26] 'Transition water' is water of a depth less than *L*/2 but greater than *L*/25, where *L* is the wavelength of the surface wave under consideration.

[27] 'Shallow water' is water of depth less than *L*/25, where *L* is the wavelength of the surface wave under consideration.

similar to the one generating the surge can be considered to establish the wind field. In this case, to establish the critical wind field, wind vectors along the critical fetches should be calculated for various times during the movement of the storm in the proximity of the site. Profiles of the wind component along the fetch should be plotted by using time variations of average wind vectors over the fetch lengths. These winds together with the average water depths for wave generation in shallow and transition water should be used as input in the calculation of offshore waves. Then the significant wave heights[28] and periods should be plotted, with account taken of the phase shift in time to allow for the generation of these waves and their travel over the fetch lengths.

6.4. When storm surges have been generated by using a stochastic approach, those storm parameters should be selected (pressure field, wind field, speed, direction and path) which could have generated the surge determined by the stochastic approach in order to use consistent storm parameters for the generation of waves. If the wave effects are to be considered jointly with a tsunami, the wind field that has a return time of a few years should be used as input for these severe wind waves. The wind speed can be evaluated by extreme methods of analysis, as described in Ref. [4]. The fetch and the appropriate orientation should be assessed by studying the regional meteorology and the characteristics of the storm that can be associated with the evaluated wind speed.

6.5. For some coastal locations the effects of wind waves are the dominant consideration in relation to flooding. When this is the case, special care should be taken in selecting the appropriate input characteristics for storms to obtain the maximum effects at the nuclear power plant. Under this condition a lower than maximum storm surge may result; however, the overall flooding would be maximized.

GENERATION OF OFFSHORE WAVES

6.6. From the selected wind field, the deep water, transition water and shallow water waves should be evaluated. In simplified methods for such an evaluation it is assumed that wind is unidirectional: these methods are based on semi-empirical relationships and use as input the fetch, wind speed and wind duration

---

[28] The significant wave height is the average height of the upper third of the wave heights in a wave record.

and, for shallow water waves, the water depth also. Where these assumptions are not valid, two dimensional spectral wave models should be used.

6.7. The generation of waves from slowly moving cyclones or storms [4] can be evaluated by methods that use as input the radius of maximum winds, the pressure differential, the forward speed of the pressure system and the maximum sustained wind velocity to calculate the significant wave heights and periods for deep water at the point of the maximum wind. Other acceptable methods are based on the use of a wave spectrum model.

6.8. The waves generated directly by the action of the wind on transition water and shallow water are also evaluated independently from deep water waves. After deep water waves have travelled into shallow water, they dissipate part of their energy and they may be reduced to such a height as not to represent the critical wave at the site. On the basis of an appropriate alignment of the critical fetch to the nuclear power plant site both deep water and shallow water waves should therefore be evaluated.

6.9. Available historical data (observed, 'hindcast' and/or measured, including satellite data) on extreme waves for the region should be reviewed to verify the results of the analysis of offshore waves.

TRANSFORMATION OF OFFSHORE WAVES

6.10. As the significant and the one per cent offshore waves are generated and propagated to the near shore area of the plant site, they will undergo dissipation and modification effects owing to the changing water depths, interference from islands and structures and other factors, and additional input of energy from the wind. The transformation and propagation of these offshore waves to the near shore area should be evaluated.

6.11. In particular, the phenomena that are relevant to this evaluation and should be considered include friction, shoaling, refraction, diffraction, reflection, breaking and regeneration.

NEAR SHORE WAVES

6.12. The near shore waves critical for the design of the plant should be identified by comparing the histories of various heights of incident deep water, transition water and shallow water waves and limiting breaking waves, with account taken of the still water hydrograph for the storm surge. An appropriate range of still water levels should be considered in selecting design wave conditions. In fact, the maximum water level and the maximum wave height can occur at different times. The arrival time of the waves is a function of the wind profile over the fetch, the group velocity of the waves and the forward speed of the storm. The time history of the limiting maximum wave heights should therefore be evaluated before the waves break owing to the effects of the reduced water depth.

6.13. A plot representing the time histories of the main wave parameters (height and period) and the maximum still water levels should be prepared for the conditions obtaining near shore by the site. A time history of the limiting breaking wave height should also be plotted. The design envelope for the near shore wave height derived from the critical wave heights expressed as a function of time should be prepared. This design envelope should be limited by the time history of the incident wave (shallow water, transition water or deep water wave), but in no case can it be higher than the significant wave height. Potential changes in bathymetry due to wave actions should be investigated because of their influence on waves.

6.14. Available historical data on observed extreme waves for the region should be reviewed to verify the results of the analysis of near shore waves.

LOCAL MODIFICATIONS OF WAVES

6.15. For each structure, system or component important to safety that is potentially exposed to coastal water action, the characteristics of the design wave should be evaluated from the selected near shore waves, with account taken of the propagation of these waves to the base of the structure. This evaluation consists of:

(a) The selection of an appropriate spectrum of incident waves and its upper limit (wave height, period and approach direction) corresponding to the various times during the approach and passage of the storm[29]; a proper two dimensional wave model should be used for this purpose.

---

[29] In calculating the maximum wave periods a value of 1.2 times the significant wave period is normally used for deep water; for calculation of the minimum wave period, the limitation of wave steepness in shallow water is appropriate. The significant wave period may be taken to be approximately the same as the average wave period. The peak period of the waves in shallow water can be up to twice the mean period.

(b) The evaluation of any additional increase in the computed still water level for a storm surge from such effects as wave set-up[30], swells and local storm effects. These effects can modify the characteristics of the near shore design wave and the resulting flood levels against structures important to safety. The extra water set-up will further increase the wave heights.

(c) The evaluation of any local modifications of waves resulting from the continuing influence of the effects of transformation of offshore waves and the evaluation of local modifications of waves due to such effects as wave transmission, runup and overtopping, including wave spray.

WAVE FORCES

6.16. The hydrostatic and hydrodynamic loading on structures important to safety should be evaluated. The nature and breaking mechanism of the waves for the given site conditions and for the entire range of water elevations that are expected should be identified, with account taken of the types of structure and the type of wave action. Both horizontal and vertical (uplift) forces should be calculated by accepted methods. When important results of analytical methods are questionable, studies should be carried out using physical models to estimate these forces. Since it is possible that the maximum loading conditions will occur at a time other than that of maximum flooding, the loading conditions should be determined over a sufficient time span during site flooding to ensure that the maximum loading conditions have been obtained.

6.17. The selection of the design wave for structural stability depends on whether the structure will be subjected to the attack of non-breaking, breaking or broken waves. For rigid structures the design wave is generally based on the one per cent wave height[31]. For semi-rigid structures the design wave should range between the one per cent wave and the significant wave, and for flexible structures it can be the significant wave. However, exposed items important to safety should be capable of performing their design functions during the occurrence of the one per cent wave.

---

[30] The wave set-up is the temporary buildup of water level at a beach due to the action of waves, which is to be added to the surge height.

[31] The one per cent wave height is the average height of the upper one per cent of the wave heights in a wave record.

6.18. Forces due to non-breaking waves are primarily hydrostatic. Broken and breaking waves generate additional forces deriving from the dynamic and impact effects of turbulent water and the compression of entrapped air pockets. Appropriate methods should be used for the evaluation of forces due to breaking waves, whereas forces due to broken waves are a combination of hydrostatic and hydrodynamic forces, which may be handled by simplified methods combining hydrostatic and hydrodynamic methods.

7. FLOODING BY SEICHES

7.1. Significant oscillations of a water body (seiches) can be excited by storm surges, variations in wind speed, tsunamis, landslides into water, underwater volcanic eruptions and other broadband disturbances (such as a local seismic displacement that could produce an extreme 'sloshing' of the entire basin). Oscillations of the water body may also arise from the continuous application of an excitation either to the water column at an entrance or over the water surface. The simplest example is that of a train of long period waves arriving at a coastal embayment, inducing oscillations of similar period. When the frequency of the incoming waves matches that of one of the local oscillation modes, a resonant amplification leading to large motions may occur.

7.2. The modes of oscillation depend solely on the surface geometry and bathymetry of the water body and the amplitudes of the oscillation will depend on the magnitude of the exciting force and on friction. Provided that the forcing action is properly specified, the modes and amplitudes of the oscillation should be calculated.

7.3. When a site is located on the shore of an enclosed or semi-enclosed body of water, the potential for seiches should be taken into consideration. If there is a potential for seiches, the probable maximum seiche should be evaluated.

7.4. If the potential for seiches derives from the action of the probable maximum storm surge on a body of water, this surge is the input for evaluating the probable maximum seiche.

7.5. If the potential for seiches is associated with the action of the wind or a pressure field on a body of water, a probable maximum storm whose parameters are maximized for the production of seiches should be established by a procedure similar to those used for evaluating the input for the probable maximum storm surge.

7.6. If the potential for seiches is associated with a landslide or seismic excitation, a reasonable upper limit for the landslide into the water or for the seismic excitation should be established by methods of the type described in Ref. [3].

7.7. Numerical models have been developed for calculating the probable maximum seiche in the form of the amplitude of oscillation as a function of time at any point within a bay of arbitrary shape. These models usually require as input a specification of the overall geometry (bathymetry and coastal topography) and of the forcing wave system. They also require as input the time dependence of the excitation (tsunami wave, surge wave, wind wave etc.) at the open boundary or source location. The amplitude time history of the seiches for the location of the plant should then be calculated. Hydraulic model studies and/or field results should be used to validate the calculation model selected.

7.8. If extensive historical observations of the oscillation of the water levels of the basin are available, the evaluation of the probable maximum seiche should be based on a stochastic processing of the data. A stochastic processing of the data can only be done if records of these observations or measurements are available for the vicinity of the plant site and if all the forcing actions for which there is a potential in the basin are adequately represented in the data. The results of the stochastic evaluation should be verified by a simplified deterministic method.

8. FLOODING DUE TO RUNOFF

GENERAL

8.1. The most common type of flood results from the runoff of rain or of melted snow and ice, or a combination of these, towards the site. Runoff occurs when the amount of water from precipitation falling or melting in a given period exceeds the losses of water by evaporation, transpiration, interception (such as by the leaves of trees), infiltration into the ground and storage in depressions in the ground.

8.2. If there is a potential for flooding due to precipitation, the following flow parameters and relevant variables should be calculated as a preliminary to the definition of the flood hazard for the site:

(1) Flow: the peak flow and the flow time history of the entire flood event (flow hydrograph).
(2) Water level: peak water level and water level hydrograph. It should be noted that, in some cases, the peak level does not occur at the same time as the peak flow (e.g. if jams of debris occur).
(3) Variations in flow and water level: hydrographs (if hydrographs are not developed, the maximum variations of the flow and of the water level, both rising and declining, should be estimated).
(4) Velocity: usually the mean velocity is readily available from the flow and the stream cross-sections. In many cases, however, estimates of the velocities at specific parts of the cross-sections are necessary for analysing dynamic effects and estimating degradation or aggradation.
(5) Channel stability: the effect of floods on the shape and elevation of the bed and banks of the channel, both during and after the flood event.
(6) Sediment transport: the suspended sediment and the bed load.
(7) Ice conditions: frazil, anchor and surface ice and ice jams.

DETERMINISTIC METHOD

8.3. The deterministic method is the preferred approach for estimating the flood hazard resulting from runoff when historical discharge series for the site are not representative. In this approach the flood hazard is derived from the design basis precipitation[32] by means of a deterministic simulation. The design basis precipitation is evaluated from the precipitation hazard, estimated according to Ref. [4], after definition of the required probability of exceedance. The conditions that generate runoff are evaluated on the basis of an analysis of the meteorological, hydrological and physiographic characteristics of the basin. The unit hydrograph method may be used to calculate the flood hazard from the design basis precipitation. The design basis precipitation and the conditions

---

[32] Design basis precipitation is the estimated depth of precipitation for a given duration, drainage area and time of year, for which there is a specified probability of exceedance. The design basis flood for a given duration and drainage area should approach and approximate the maximum value that is considered to be physically possible.

generating runoff should not be estimated by a single method but by a set of methods and processes of transposition, maximization and estimation of coefficients in which the hydrologist and meteorologist together apply their judgement[33]. In this work the contributions of experienced experts are essential to reduce the uncertainties to an acceptable level.

8.4. The positions of the storms over the basin should be selected in such a way that the maximum runoff (in terms of volume or peak water level, whichever is critical) will occur.

8.5. In basins where snow melt can contribute significantly to the flood hazard, special consideration should be given to the maximization of a combined event of rain plus snow melt. To compute the maximized contribution of snow melt to the flood in such basins, the seasonal accumulation of snow should be maximized and a critical melt sequence should be selected. A design basis precipitation event appropriate to the time of year should then be added to the maximized snow melt event, and the additional snow melt due to the precipitation (if it is rain) should be included.

Losses of water

8.6. Losses of water should be estimated by comparing the incremental precipitation with the runoff for the recorded storms. Usually losses are expressed as an initial loss followed by a continuing constant loss over a period of time[34].

---

[33] Both larger and smaller areas have been used in practice in the derivation of unit hydrographs. Upper limits of gauged areas ranging from 1000 to 8000 km^2 have been used. For ungauged areas, some experts believe that areas as large as 20 000 km^2 can be justified. The use of areas as large as 20 000 km^2, if gauge data are not available, can be justified because the errors introduced in this way will not be greater than those resulting from the estimation of the unit hydrographs of subareas and the routing of the flows from the subareas.

[34] For example, typical losses might be an initial loss of 10 mm, followed by a continuing loss of 2 mm per hour. It is often not worthwhile making detailed studies of losses because their effect on flood peaks may be insignificant. If, for example, the maximum hourly increment of the design basis precipitation is 150 mm, the effect of a loss of 2 mm per hour on such rainfall is insignificant compared with the errors inherent in the other parameters.

8.7. Erosion and sedimentation during the flood may be ignored. However, where the type of channel bed indicates that erosion may lead to increased roughness, the hypothesis of higher roughness during the peak of the flood and immediately afterwards should be taken into consideration. Variations in depth and in roughness in the cross-section and the possible presence of ice as a total or partial river cover should be considered where appropriate. Partial constrictions such as bridges are considered to be a complete obstruction during the flood and accepted, where appropriate, as control points, if these assumptions are conservative.

8.8. When two sequential storms are postulated, the losses for the second storm should be assumed to be less because of increased ground wetness. In many cases, losses are ignored, which is the most conservative approach.

Unit hydrographs or other rainfall runoff models

8.9. The unit hydrograph is the runoff hydrograph that would result from unit rainfall uniformly distributed over the basin in unit time. Typically, it might represent the hydrograph resulting from an excess rainfall increment of 10 mm in one hour. The time increment may be decreased or increased, depending on the size of the drainage area. In practice, unit hydrographs should be developed for rainfall patterns that are not uniform. Where orographic factors produce fixed but non-uniform patterns, the unit hydrograph should be developed for the pattern typical for large storms in the basin.

8.10. The unit hydrograph should be derived from recorded flood hydrographs and their associated rainfall.

8.11. Unit hydrographs derived from small floods may not represent the true flood characteristics of the basin when applied to large storms. This is because the assumption of linearity for the unit hydrograph model is not always valid since the hydraulic efficiency of the basin increases with increasing runoff only up to a certain limit and also since changes in channel flow from within bank to out of bank may occur. Unit hydrographs based on floods representing excess precipitation of about one third or more of the maximum precipitation level should be accepted as derived without adjustment for non-linearity. For smaller floods, methods have been developed for adjusting the unit hydrographs for non-linearity; where only small floods are of concern, such methods of unit hydrograph derivation may be applied. It may also be possible to estimate the non-linearity by comparing the unit hydrographs derived from floods of various sizes.

Base water flow

8.12. The ambient water flow in the stream at the time of the postulated occurrence of the design basis storm sequence should be estimated. The base water flow should be reasonably representative of the season of the year and the period of time during which the reference storm selected on the basis of the design basis precipitation may be expected. No great efforts should be expended in determining the base flow to a high accuracy, since this is usually only a small percentage of the flood runoff.

Flood routing

8.13. Flood routing should be carried out; this is the process of determining the characteristics of a given flood at the point of interest when the flood characteristics at a location upstream from the point of interest are known.

8.14. A validated model of the river channel through which the flood should travel is used. Flood routing methods are often divided into:

- Hydrological routing methods which use the equation of continuity only (storage equations),
- Hydraulic routing methods which additionally take dynamic effects into account.

8.15. These methods yield values of the flow. The model to be used to convert these values into water levels should be based on either steady or unsteady flow. For floods with a relatively small rate of change of flow or of stage, steady flow routing will approximate the channel flow rates with sufficient accuracy. Unsteady flow routing should be applied when the variation in flow is very significant as it simultaneously computes the time sequence of both the flow and the elevation of the water surface over the full length of the water stream.

8.16. Routing a flood through a reservoir is a special case of channel routing and it is usually approximated by steady flow methods. Where it is necessary to divide a watershed into subareas, runoff models should be connected and combined by means of stream course models.

Flood level

8.17. In the evaluation of the flood level, consideration should be given to the existence of structures in the flood channel that may give rise to backwater phenomena. Backwater computations may be carried out by using analytical or graphical techniques.

8.18. The maximum rates of change of flow and of level can be read directly from the hydrograph for maximum flow and level. It should be noted that periods of maximum increase or decrease in flow may not coincide with the corresponding periods of maximum increase or decrease in level. If these parameters are critical for the design of certain structures important to safety such as levees, consideration should be given to the possibility that small area precipitation on sub-basins of the watershed may lead to faster rates of increase or decrease in the level.

Water velocity

8.19. Floods may affect safety not only via water levels but also via the effects of the water velocity. Water velocities could be derived directly from backwater and routing computations. However, if increased roughness coefficients have been considered for the conservative estimation of levels, adjustment to the roughness coefficients to obtain conservative values of the velocities and related levels should be considered. In situations for which mathematical models are difficult to develop, for example where river channels are complex and velocities may be high enough to affect structures important to safety such as levees or fills, dedicated models for estimating the design velocities should be constructed.

Sedimentation and erosion

8.20. The analytical techniques currently available, even if supported by measurements, are incapable of providing reliable estimates of sedimentation, erosion conditions and related changes in channel morphology during and after extreme flood conditions. If the safety features of the plant are affected by sedimentation or erosion, a physical–hydraulic model should be constructed to study these phenomena. In some cases it may be possible to check the results by means of a mathematical model. In a desert–mountain environment, the potential for mud flows should be considered.

Floating debris, logs and ice conditions

8.21. The effects of obstruction of the channel by floating material may be very difficult to predict analytically. If the safety features of the nuclear power plant are affected, a physical–hydraulic model should be constructed to study these phenomena.

8.22. Particularly, an ice jam can result from the compacting of locally formed ice by wind, by water currents or by the drifting of sea ice into an estuary or river. Where a proposed site is near an estuary or river, historical records should be analysed to ensure that structures and systems important to safety could not be adversely affected by the presence of ice (including sea ice) and to provide data for assessing the flood hazard. The following scenarios should be considered for the evaluation of the design basis conditions:

(a) Water backup caused by ice cover and ice jams;
(b) Forces on dams, intake structures, gates and control equipment due to ice;
(c) Blocking of intake screens, pumps, valves and control equipment by ice;
(d) Ice ridging on enclosed bodies of water;
(e) Jamming caused by slides of ice and snow;
(f) Waves or seiches caused by slides of ice and snow.

8.23. In addition to blocking intakes and affecting flood levels, ice can exert dynamic and static forces on structures. Records should be examined to establish the potential thickness of the ice, the concentration, frequency and duration of the buildup of ice, and the normal and extreme periods of the ice season. These data are used to make a conservative estimate of the probable maximum thickness of the ice. Structures should be designed to be capable of sustaining the probable maximum ice loading.

PROBABILISTIC METHODS

8.24. Probabilistic (stochastic) methods may be suitable for determining the flood hazard provided that sufficient and reliable data are available for discharge series at the site or at gauges on the river in the basin of the site. Stochastic methods should be a substitute for deterministic methods in cases for which the data on meteorological variables are scarce but hydrological records of significant length are available at the site or at several hydrometric stations in the region. The conservativeness of the method should be proved.

9. FLOODING DUE TO SUDDEN RELEASES OF WATER FROM NATURAL OR ARTIFICIAL STORAGE

GENERAL

9.1. Natural or artificial storage of large volumes of water may exist upstream of a site. Water may be impounded by a human made structure such as a dam for power generation, irrigation or other purposes or by temporary natural causes such as a jam of ice or debris that causes an obstruction in a river channel.

9.2. The failure of such water retaining structures (the probable maximum dam break) due to hydrological, seismic or other causes, such as a landslide into a reservoir or the deterioration of a dam with time, may cause floods in the site area.

9.3. Hydrological failure of natural or artificial storage is due to insufficient spillway capacity compared with the water inflow into the reservoir, either because of faulty operation or because the water inflow exceeds design values. This causes an increase in the water level and the dam may be overtopped. In the case of an earthfill or rockfill dam, overtopping would cause the failure of the dam.

9.4. The basic and most important difference between a flood due to precipitation and a flood due to the failure of a water control structure, whether natural or human made, is that the latter may generate a wave of great height moving downstream at high speed. A considerable dynamic effect may thereby be exerted on the site and on the structures built on it and the site should therefore be evaluated.

9.5. In the site selection phase, all upstream dams, existing or planned, should be considered for potential failure or faulty operation. Some may be eliminated from consideration because of their small storage volume, distance from the site or low differential head, or because of a major intervening natural or artificial capacity for water retention[35]. A detailed investigation, as outlined

---

[35] Some Member States consider systematically the collapse of each large dam upstream of the plant, evaluate the one critical for the site level and assess the wave which results from the collapse of this dam associated with the collapse of all the dams located downstream of the dam as far as the plant.

earlier (para. 8.3), should be performed of the drainage area upstream of the site to determine in which sections the formation of a natural channel blockage is possible, with account taken of the fact that human made structures, such as mine waste dumps, highway fills across valleys or low bridges, may act as dams during floods.

9.6. Dams located on tributaries downstream of the site should be taken into consideration if their failure could increase the flood hazard at the site.

9.7. No reduction of flood level at the site due to the failure of a downstream dam should be claimed unless it can be demonstrated that the dam would certainly fail.

HYDROLOGICAL DAM FAILURES

9.8. Dam failure should be postulated unless non-failure can be demonstrated with the required probability of exceedance by means of engineering computations.

9.9. Dams whose failure may give rise to the controlling flood at the site should be assessed for failure under two major hypotheses:

(1) The design basis precipitation isohyetals are critically centred in the basin upstream of the dam.
(2) The design basis precipitation isohyetals are critically centred in the entire basin above the site.

In both cases the design basis precipitation isohyetals should be selected to produce the maximum floods — in the first case at the dam, in the second case at the site.

9.10. Since it is generally very difficult, expensive and time consuming to determine and to demonstrate, on a quantitative basis, the safety and stability of a dam (structural, hydrological or otherwise), it may be more efficient to make a simple conservative analysis on the assumption of the collapse of the dam; if this conservative analysis shows no significant effects at the site, further more detailed analyses are unnecessary.

9.11. If it can be demonstrated that a dam can survive this flood on the basis of hypothesis (1), no further analysis should be made except that related to the failure of upstream dams. If not, the degree and mode of failure should be estimated, and the resulting flood wave, combined with the downstream flows that would be produced in this flood, should be routed to the site. If the watershed controlled by the upstream dam is a major part of the total site watershed, the parameters of the design basis precipitation used for computing flows below the dam should be estimated from the outer isohyetals of the design basis precipitation pattern or from extending the depth and/or area curves used to evaluate the stability of the dam. If it is judged that an upstream dam would fail owing to its own watershed, the potential for failure should also be examined for the flood hazard applicable to the total watershed of the site (hypothesis (2)). If the dam is judged to fail in either case, the resulting flood wave should be routed downstream to the site for comparison and selection of the critical case.

9.12. A dam which would otherwise be safe in the event of design basis precipitation may fail as a result of such a flood augmented by the flood wave generated by a hydrological dam failure upstream. An analysis of the integrity of all dams along the path to the site should be performed and unless non-failure can be established failure should be postulated. Floods resulting from all assumed dam failures should be routed to the site. If several dams are located on various tributaries, the physical possibility and, when appropriate, the probability and the consequences of the flood waves arriving simultaneously at the site should be considered.

9.13. It is recognized that floods originating from dam failures could be increased by flood waves due to landslides into rivers and reservoirs, which could result from severe precipitation. Floods caused by dam failures should generally be combined with an appropriate flood due to other causes (see below) to obtain the controlling flood. The appropriate coincident wind wave activity (wave set-up and wave runup) should be superimposed on the flood still water level that has been determined.

Postulation of failure

9.14. If the non-failure due to flood water of a dam cannot be demonstrated, the mode and degree of failure should be postulated using conservative judgement based, to the extent possible, on stability analysis. In the postulation of the failure mode, account should be taken of the type of construction of the dam and the topography of the river channel immediately downstream of the dam.

9.15. Concrete gravity dams should be analysed against overturning and sliding; the mode and degree of the probable failure should be judged together with the most critical positions and amounts of downstream fragments. From this analysis, as applied to the postulated failed section, it should be possible to estimate the water path and the likely elevation and flow relationship with reasonable accuracy.

9.16. Arch dam failure is likely to be practically instantaneous and the destruction of the dam may be total. Consequently, unless non-failure can be demonstrated, instantaneous and complete failure of the arch dam with no appreciable accumulation of fragments downstream should be postulated.

9.17. For rock or earthfill dams, failure takes a longer period of time than for concrete dams. The time for the total collapse of the structure may range from a few minutes to several hours. The failure of a rockfill dam may take a considerably longer time than the failure of an earthfill dam. In making erosion calculations to determine the time and rate of failure, an initially breached section or notch should be postulated. These computations should also yield the outflow hydrograph.

9.18. Where it is impossible to determine a non-negligible time period for the collapse of an earthfill dam, instantaneous and total failure should be postulated.

Failure outflow hydrograph

9.19. The outflow from a partially failed non-embankment dam depends on the degree and mode of failure, the resulting headwater and flow relationship, and the geometry and volume of the reservoir. Unsteady flow methods are the most suitable for downstream routing of dam failure surges and these should therefore be applied. Where distances are considerable, however, and if the intervening channel or reservoir storage can be shown to attenuate surge flows adequately, less complex storage and flood routing may be used in the model.

SEISMIC DAM FAILURES

9.20. Flooding can result from dam failures (upstream or downstream) caused by seismic events or from the consequences of seismic events such as a landslide into a reservoir. Failures may occur of both human made dams and naturally created water impounding structures.

9.21. Any proposed site is required to be evaluated for the potential consequences arising from a seismically induced failure of any dam upstream or downstream that could affect floods at the site [1]. If the evaluation reveals potentially unacceptable consequences, then the potential for dam failure should be assessed.

9.22. The seismic analysis of dams requires consideration of the dynamic loading; furthermore, a detailed stability analysis requires proper documentation of the condition of the structure. Inspection reports issued by the appropriate national technical bodies should be used in the stability analysis. Additional data should include the results of strength tests of the dam foundation areas, field surveys and inspection by other bodies, together with pertinent data collected by instrumentation installed at the dam site.

9.23. For the seismic analysis of each dam, an appropriate earthquake (see Ref. [2]) should be derived, specifically for the dam site or the landslide site.

9.24. The possibility of the failure of two or more dams being caused by the same seismic event should also be taken into consideration. If there is a potential for common failure, the possible simultaneous arrival of the flood peaks should be considered, unless it can be demonstrated that the times of travel of the peaks are sufficiently different for their simultaneous arrival to be impossible.

Postulation of failure

9.25. Most of the procedures described in the previous subsection may be applied to seismic failures. However, for failure models for hydrological dam failures it is assumed that the dam is overtopped by water, while for seismic failure this does not necessarily occur. The mode and degree of failure should be postulated by using conservative judgement based as far as possible on stability analysis.

9.26. The seismic effects on dam appurtenances should be analysed with regard to reservoir surcharge and the resulting instability of the dam or its breaching by overtopping. The sudden failure of gates due to seismic action should also be postulated for its resulting downstream flood wave.

9.27. In the detailed analysis, the forces usually taken into account in dam design should be taken into consideration as loads for dam break stability analysis in addition to the dynamic components of earthquake forces. Such loads may include:

- dead load,
- external water pressure,
- uplift (internal water pressure),
- earth and silt pressure,
- effects of ice in the reservoir,
- floating objects (other than ice),
- wind pressure,
- subatmospheric pressure,
- wave pressure,
- the reaction of foundations.

Routing of the resulting flood, if the failure is postulated, can be performed according to the methods mentioned in the previous subsection.

DAM FAILURES RESULTING FROM CAUSES OTHER THAN HYDROLOGICAL AND SEISMIC

9.28. Water retaining structures may fail as a consequence of causes other than those mentioned in the previous subsections. Examples are:

- the deterioration of concrete or of the embankment protection;
- excessive or uneven settlement with resultant cracking;
- piping and seepage;
- foundation defects;
- leakage through foundations, the embankment rim or passages (‘through conduits’) brought about by the action of the roots of vegetation or burrowing animals;
- functional failures such as failures of gates;
- the accumulation of silt or debris against the upstream face;
- a landslide into the reservoir.

9.29. As a rule, these on-site causes may result from gradual changes in, under or adjacent to the dam. Proper inspection and monitoring should be carried out to detect these gradual changes early enough for adequate corrective measures to be taken. As an essential safeguard against the possibility of landslide induced floods at the site, studies should be made of the ground along the slopes of the terrain around the reservoirs to determine the potential for landslides that may affect the reservoirs directly.

FAULTY OPERATION OF DAMS

9.30. The faulty operation of dam facilities can create floods that may occasionally exceed naturally caused floods. An investigation of upstream dams in this regard, particularly those with gates capable of controlling large flows, should be made to assess the magnitude of possible water releases and to investigate the potential for faulty operation. In this investigation, the possibility of faulty or abnormal operation caused by emergencies, by human error, by the abnormal functioning of automated systems and by erroneous information or the erroneous interpretation of information about inflows into reservoirs should be investigated. The possibility of the simultaneous faulty operation of two or more dams should be taken into consideration if there is a reasonable likelihood that the causes of faulty operation may coincide or may occur within a short period at these dams.

10. FLOODING DUE TO OTHER NATURAL CAUSES

GENERAL

10.1. If there is a potential for flood conditions being caused by or affected by the following phenomena, the effects on safety should be investigated and taken into account by using one of the methods described in the previous sections:

- phenomena attributable to icy conditions (backwater upstream),
- landslides or avalanches into water bodies,
- log jams or jams of floating debris (backwater upstream),
- volcanism.

CHANGES IN NATURAL CHANNEL

10.2. From time to time river channels may change their configuration or alignment as a result of natural processes. If there is a potential for these phenomena, the influence on flood conditions should be investigated and any possible effects on safety should be taken into account.

DIRECT RAINFALL ON THE SITE

10.3. The precipitation falling directly on the site should be investigated as a potential cause of the most severe drainage load at the site and the effects should be taken into account in the design of the site drainage system. The site drainage system should be designed for such amounts of precipitation so that rainfall (combined with snow or hail, if necessary) will not cause ponding, the overflow of ditches or conduits or flooding due to other causes. Details of such a hazard evaluation are provided in Ref. [4].

10.4. The fact that this major drainage load is likely to occur simultaneously with flood conditions should be taken into account in the design of the drainage system. In addition, the effect of the local precipitation on the roofs of buildings important to safety should be studied. Roof drains are usually designed to discharge rainfall at intensities considerably less than those of the design basis precipitation. Since the roof drains may be obstructed by snow, ice, leaves or debris, buildings with parapets may pond water (or combined water, snow and ice) to such a depth that the design load for the roof will be exceeded. Several methods can be used to cope with this, among which are the omission of parapets on one or more sides of the building, limiting the height of the parapet so that excess ponded water will overflow, installing scuppers through the parapet and heating the roof to prevent the buildup of excessive amounts of snow and ice.

WATERSPOUTS

10.5. In some parts of the world, notably in the tropics, waterspouts may transfer large amounts of water to the land from nearby water bodies. Such events are usually of short duration and cover relatively small areas [4]. If there is a history of waterspouts in the region the associated precipitation should be taken into account in the design of the drainage system.

11. TSUNAMI FLOODING

GENERAL

11.1. A tsunami is a train of water waves generated by impulsive disturbances of the water surface due to non-meteorological but geophysical phenomena such as submarine earthquakes, volcanic eruptions, submarine slumps and landslides or ice falls into a body of water. The severity of the waves at the nuclear power plant will depend on the characteristics of the seabed movement, the location of the plant (whether it is near a fjord or bay) and the direction of movement with respect to the plant, and the response of the near shore waters to the tsunami waves. Depending on its location, the site might be subjected to damaging waves.

11.2. Tsunami generating events and the initial coupling of the events to the water are not well documented in the literature and there is still much research work to be done. Sites that are not severely affected by tsunamis should therefore be preferred. However, if a nuclear power plant is to be located in an area that could be subject to tsunamis, a conservative analysis of the potential effects produced by tsunamis should be performed and the plant should be designed for a design basis flood with a probable maximum tsunami taken into consideration. In certain cases also a severe tsunami having a given mean return time should be considered in the combination of events for evaluating the design basis flood. The assessment of the probable maximum tsunami should be sufficiently conservative in nature to ensure that the plant will be adequately protected against all the potential effects of a tsunami.

EARTHQUAKE INDUCED TSUNAMIS

11.3. A tsunami is called a local tsunami when it affects the region near its source where the vertical deformation of the sea bottom generates the water wave. A local tsunami has many components of different wave period, reflecting the characteristics of its initial profile. The dominant wave period usually ranges from 3 to 30 minutes. A similar tsunami that arrives at remote places after travelling across the ocean is called a distant tsunami. During its travel, the short period components of the wave train are scattered by islands and sea mounts. The dominant wave period of a distant tsunami is usually longer than 30 minutes.

11.4. When a tsunami is generated in or near the continental shelf, it will have many wave components of differing frequencies. For a local tsunami, the dominant wave period will be from 3 to 20 minutes. For a distant tsunami, the dominant wave period is usually longer than 30 minutes because shorter period components of the wave train are damped out during the travel for long distances over the ocean.

11.5. The potential for events that generate tsunamis (both distant and local) should be determined by using the results of geological, tectonic and seismic investigations and making an analysis of historical data. If there is such a potential, the probable maximum tsunami generated from the worst case of either specified distant geoseismic activity or local geoseismic activity should be determined. The analysis of the effects of a probable maximum tsunami at a nuclear power plant site should be made on the basis of an estimation of the water motions that would develop from postulated seabed displacements. The resulting wave train systems or water motions should be assessed for the purpose of determining their near shore and onshore effects. In evaluating the runup and drawdown at the shoreline due to tsunamis, the effects of the local offshore and coastal topography should be considered.

11.6. If it is available, historical information such as records of runup heights, tide gauge records and reports of observed tsunamis and the damage they caused should be used to assess the validity of the computational methods used for determining the near shore effects of tsunamis. The justification of the analytical methods presented for determining the probable maximum tsunamis should be supported to the extent possible by evidence of satisfactory agreement with data from observations, but in any case the results should be demonstrated to be conservative.

11.7. The simplest way of estimating the initial profile of a tsunami generated by a submarine earthquake is to assume that the displacement of the sea bottom is a result of the fault movement in a semi-infinite elastic homogeneous body. A fault movement is characterized by its location, including its depth, geometrical characteristics (the strike, dip and slip angles of the fault plane), physical characteristics (the length, width and dislocation of the fault plane) and dynamic characteristics (the rupture direction, rupture velocity and rise time of the fault movement). The static displacement of the sea bottom should be computed by using these fault parameters (except for the dynamic characteristics). A tsunami hazard should therefore be evaluated by methods similar to those described for seismic hazards in Ref. [2]. An earthquake should be postulated to occur along the potential ‘tsunamigenic’ tectonic structures and in the seismotectonic province where it would produce the worst tsunami at the site. The following information is required for adequately defining the vertical seabed displacement and the resulting elevation of the water surface:

- the magnitude of the earthquake,
- the maximum vertical ground displacement,
- the length and width of the source,
- the orientation and shape of the source,
- the length of the fault rupture and the location of the epicentre,
- the decay of the displacement with distance from the fault.

11.8. Some of these data may be obtained from the investigations made to evaluate the seismic hazard as described in Ref. [2]. A conservative determination of these data should be made using the results of geological, tectonic and seismic investigations together with the analysis of historical records.

11.9. The determination of the corresponding elevation of the water surface caused by the upheaval of the seabed should be carried out as the second step of the evaluation of the tsunami hazard. It is widely postulated with success that the initial elevation of the sea surface is the same as the static vertical displacement of the sea bottom calculated on the assumption of homogeneous dislocations on fault planes. Any application of more sophisticated techniques that include the consideration of the heterogeneity of fault movements as well as the dynamic excitation of tsunamis should be carefully validated.

NON-SEISMIC TSUNAMIS

11.10. Landslides, ice falls, submarine slumps and volcanic eruptions are secondary causes of tsunamis, some of which are more disastrous than earthquake induced tsunamis. Since the movement of mass in a landslide into water generates a tsunami wave, the volume and dynamics of the landslide such as the duration in time and the velocity and/or rate of discharge should be determined to estimate the landslide induced tsunami. Provided that information on the mass movement and the boundary conditions is inserted into the numerical model, the generation and propagation of the tsunami can be simulated. For a volcanic tsunami, three generation mechanisms should be considered. The first is the impact of falling rocks after ejection into the air. The second is the underwater vapour explosion which results in a rapid rise of the water surface. The third is the formation of a caldera which causes the surrounding water to rush into the cavity produced by the caldera.

DISTANT TSUNAMIS

11.11. In most cases, the propagation of the wave system resulting from a distantly generated tsunami can be treated in a simplified manner. Tsunami waves of short period are more easily damped by friction and breaking; only front running waves of longer period should therefore be considered at a coastal site located at a great distance from the source generating the tsunami.

11.12. Because its wavelength is much greater than the depth of the water, the tsunami gives rise to a system of long linear waves. From its generation in deep sea to its travel over the ocean, a distant tsunami can therefore be simulated with the aid of linear equations for long waves with the Coriolis force included, described in the longitude–latitude co-ordinate system.

11.13. An initial tsunami profile has many components of different periods which propagate with different velocities. This difference in velocity, although very small, results in non-negligible deformations in the wave profile if the travel time becomes long, as in the case of a distant tsunami. A parameter Pa is used to judge whether or not these frequency dependent dispersion effects should be included:

$$\mathrm{Pa} = (6h/R)^{1/3}(a/h)$$

where h is the depth of the water, a the horizontal dimension of the tsunami source and R the distance from the source to the site of the nuclear power plant concerned. If Pa is larger than 4, the linear equations for long waves with the Coriolis force included, described in the longitude–latitude co-ordinate system, can be used. If Pa is smaller than 4, the frequency dependent dispersion effects should not be neglected. Under this condition, the linearized Boussinesq equation which includes the first order effect of the dispersion with frequency and which is modified to include the Coriolis force described in the longitude–latitude co-ordinate system should be used.

LOCAL TSUNAMIS

11.14. If there is a potential for locally generated tsunamis, the wave system and the propagation of local waves should be evaluated. The determination of the wave system and propagation of a locally generated tsunami cannot be simplified in the same way as for a distantly generated tsunami. The long wave approximation is invalid because the short period waves are important near the generating source of the tsunami. Any simplifying assumptions made for evaluating locally generated tsunamis should be carefully and critically examined and should be used only if they can be demonstrated to provide conservative results.

11.15. If the water is deeper than 200 m, the linear long wave equation should be applied. For the region shallower than 200 m, the shallow water theory with a term for bottom friction included should be used. This shallow water theory includes the first order approximation of the amplitude dependent dispersion. Under special conditions, the term for frequency dependent dispersion should be included. If the purpose of the simulation is to determine the runup height, the equations of higher order approximations are not necessary.

11.16. Locally generated tsunami waves may propagate from their generating source to the near shore area of a nuclear power plant site; hence the phenomena of wave propagation (refraction, reflection, shoaling and diffraction) will be important. Numerical techniques should be applied to determine the modifications of the waves during their propagation. The accuracy of the topography of the sea bottom will have a vital effect on the computed results.

NEAR SHORE MODIFICATIONS

11.17. As a tsunami nears the shoreline, its height increases and becomes comparable with the water depth (‘shallow water’: see footnote 27). The shallow water equations including the effect of bottom friction should be applied. The theory still assumes the hydrostatic pressure but it takes into consideration the finiteness of the wave amplitude. The second order phase velocity includes the effect of the elevation of the water surface. This effect causes the higher part of the wave to proceed faster. The frontal slope of the wave thus becomes steeper. If the velocity of the water particles at the front exceeds the local phase velocity, the water projects into the air; consequently, a breaking bore is formed.

11.18. Significant oscillations of a water body (seiches) can be excited by tsunamis. When the frequency of the incoming tsunami matches one of the local oscillation modes, resonant amplification leading to large motions of the water may occur. Oscillations of a water body also arise from the continuous application of an excitation either to the water column at an entrance or over the water surface. The maximum wave height can therefore often be observed not at the arrival of the first wave but after several waves. To evaluate the possibility of such an oscillation, the wave period of a tsunami and the frequency of the local oscillation modes should be known.

11.19. As tsunami waves reach the shoreline or the coastal features under consideration they will experience shoaling, steepening and possibly breaking. Whether or not the wave breaks, reflection, dissipation or transmission will expend the energy contained in each wave. The primary result of tsunami waves on a beach is the runup, which is the vertical height above the still water level that the rush of water reaches. This height will depend on the geometry and roughness of the structure or beach, the water depth and the slope of the wave fronting the structure or beach, and the characteristics of the incident wave. There are a number of approximate theories and empirical relationships from which the runup can be estimated, given the characteristics of the offshore wave. Caution should be exercised to ensure that the method selected is applied within its range of validity in terms of the characteristics of the offshore waves and the beach slopes.

NUMERICAL SIMULATION

11.20. A tsunami starts with a complicated initial profile, is transformed by the effects of complicated bottom topography, and runs up and down on land of complicated topography. In estimating the tsunami hazard, it is the usual practice to carry out a numerical simulation. In order to ensure stable computation and accurate results, dedicated validation programmes should be used.

SEDIMENTATION

11.21. Since bottom shear by a strong tsunami current may be significant in shallow water, the deposition of and erosion by a large amount of sand sediment could affect the safety features of the plant. Erosion may cause the failure of breakwaters and may damage a nuclear power plant further along the coast or in a harbour. In particular, the deposition of sand around cooling water structures or the water inlet and outlet might disrupt the operation of the plant. A dedicated analysis of this effect should be carried out by measuring the characteristics of the sand near the plant and using validated mathematical models.

11.22. The three forms of tsunami waves that should be considered in estimating the forces of tsunami waves acting on structures are:

(a) Non-breaking waves (the tsunami acts as a rapidly rising tide),
(b) Waves breaking far from the shoreline (the tsunami waves become fully developed bores before reaching the shoreline),
(c) Waves breaking near the shoreline (the tsunami waves act as partially developed bores that are not uniform in height).

In estimating wave forces for cases (a)–(c), the pressures on structures of dynamic waves as well as static waves should be considered.

12. COMBINED EVENTS

GENERAL

12.1. In deriving the design basis flood for a nuclear power plant, combined events should be considered as well as single events. Combinations of events should be carefully analysed with account taken of the stochastic and non-linear nature of the phenomena. Furthermore, the ambient conditions that are relevant for the important flood causing event or for each event of the selected combination should also be taken into account.

INITIAL AND AMBIENT CONDITIONS

12.2. The following ambient conditions should be considered in the evaluation of flood causing events:

(a) Soil moisture: the median soil moisture level for the expected month of the flood (the value to be used at the start of the antecedent storm).
(b) Base flow rate: the mean flow rate for the expected month of the flood (the value to be used at the start of the antecedent storm).
(c) Reservoir level: the reservoir levels should be taken as being at the upper point of the curve given in the operating rules when the first of the flood producing events occurs.
(d) The estuary level behind a storm surge barrier.
(e) The presence of residual water in flood prone areas.

12.3. In some cases, such as for very small basins, making allowance for the antecedent storm may not be necessary because the hydrograph will have reached the base flow rate in the interval preceding the storm. In such cases a conservatively high base flow rate and soil moisture level should be used instead of making allowance for the antecedent storm. A more conservative approach is to use values for the antecedent storm together with the median soil moisture level and the mean base flow rate as the initial conditions.

COMBINED EVENTS

12.4. For evaluating combined flooding events on coastal, estuary and river sites, distinctions may be made between:

(a) Extreme events (such as storm surges, river floods, seiches and tsunamis);
(b) Wind waves related or unrelated to the extreme events;
(c) Reference water levels (including tides if significant).

12.5. Appropriate combinations of extreme events with wind waves and reference water levels should be taken into consideration. The probability range of each combination should be estimated.

Criteria for selecting combinations of events

12.6. The design basis flood for a given site may result not from the occurrence of one extreme event but from the simultaneous occurrences of more than one severe event each of which is in itself less than the extreme event. The interdependence or independence of the potential flood causing phenomena should be examined according to the site specificity. In many combinations of flood causing events the distinction between dependent and independent events is not sharp. Sequential meteorological events, for example, are only partially dependent on or fully independent of each other. In contrast, seismic and wind events are clearly independent.

12.7. At present the technology is not available for precisely assessing the numerical probabilities that a given level of severity of an effect is exceeded in each separate event or by a combination of events. However, conservative values should be estimated for the following quantities:

(a) The probability that a given level of severity of an effect is exceeded for each separate event,

(a) The likelihood that separate severe events may occur together in a combination of events.

Reasonable values of the probabilities that a certain level of severity of an effect is exceeded in the combination should be estimated from the values for these quantities. In this way, the combinations of events causing flood effects from which the nuclear power plant should be protected should be identified. In this estimation, care should be taken in estimating the duration of the occurrence of the severe level for each event.

12.8. For independent events, the probability that they will occur in such conditions that their effects will be cumulated is related to the duration of the severe level of each event. The probability that the events occur in combination is less than the product of the probability of each event and the effect of contemporaneous events should be considered (see example B in the annex).

12.9. The greater the number of independent or partly dependent events that are considered in combination and the greater the magnitude of each event, the lower will be their combined probability of exceedance. Protection of a nuclear power plant against an excessive number and severity of events in combination may result in over-conservative values for the design basis flood.

12.10. The events to be combined should be selected appropriately with account taken not only of the resultant probability but also of the relative effect of each secondary event on the resultant severity of the flood. For example for estuary sites, combinations that should be examined should include both maritime and river conditions. If the consequences of these combinations are significant and the combined probability of the results is not very low, they should be taken into account. Considerable engineering judgement is necessary in selecting the appropriate combinations (see the annex for examples).

Application of the criteria

12.11. For coastal and river sites the flood events that should be considered usually include the effects from single initiating causes and the effects from a combination of initiating causes. The following causes should be examined:

- surge,
- seiche,
- tsunami,
- runoff,

- dam break,
- wind waves,
- ‘other causes’.

12.12. An acceptable value for the limiting annual probability of exceedance should be established for the combinations of extreme events and the relevant reference water levels that are to be taken into account in deriving the coastal design basis flood for a nuclear power plant. Certain combinations of events can be excluded from consideration if:

- The postulated combination does not produce a combined load on some part of the plant,
- The combined probability is equal to or less than the established limit for the probability value,
- The combination is not physically possible.

12.13. Wind wave activity should be considered in association with all the flood events. In a surge or a seiche wind waves are a dependent event and the waves that are generated by the storm that is producing the surge should be considered. In some coastal regions wind generated waves might constitute the major flood event and the associated surge component may be of less importance. In these cases special care has to be exercised in the assessment of wind wave effects and in the selection of appropriate combinations of flood causing events. Tsunamis and river floods are usually independent events; the coincidental occurrence of severe wind waves may also be disregarded. Only wind waves with a shorter recurrence interval should be considered in the combination. In general, account should be taken of the possibility that wind is a dependent variable accompanying the high river flood or the meteorological conditions generating the flood.

12.14. A seiche may be excited by such causes as fluctuations in barometric pressure, storm surges, variations in wind speed and the random wave background. Thus the excitation of seiches may depend on the other flood causing events discussed in this Safety Guide. This fact should be taken into account in selecting the appropriate combinations for a site where seiches can be important. Possible combinations of flood causing events are given in the annex.

12.15. The potential for instability of the shoreline, jams of debris and ice effects should be evaluated and if the occurrence of these events affects the flood at the site they should be combined with other primary flood causing events.

12.16. The possible indirect effects on plant safety of the flood causing events should also be investigated. These effects could include, for example, injuries to plant personnel, damage to structures caused by debris carried by the flood or the in-leakage of groundwater resulting from a rise in the water table due to the high level of surface water near the site.

13. ASPECTS OF FLOOD PROTECTION FOR COASTAL AND RIVER SITES

GENERAL

13.1. Considerations in plant design should include:

- Evaluation of the design parameters for structures built for the protection of the site area, such as dams and levees;
- Evaluation of the effect of raising the site area above the calculated flood water level;
- Selection of the best possible materials for resistance to the erosive effects of the water;
- Evaluation of the most appropriate layout of the plant for protection;
- Study of possible interference between the structures for protection and parts of the plant.

13.2. Any human implemented measures for protection (such as dam structures, levees, artificial hills and backfilling) can affect the design basis for the plant. Such protection is included in the present framework for site evaluation even though in principle its safety function could be considered in the relevant Safety Guides for plant design. The so-called ‘incorporated barriers’ directly connected with the plant structures (special retaining walls and penetration closures) are dealt with in Ref. [3] since they are not considered part of the site protection measures as such.

13.3. Both external barriers and natural or artificial plant islands should be considered features important to safety and should be designed, constructed and maintained accordingly.

13.4. A study of the protection measures should be performed once a complete understanding of the hydraulic and geological environment of the site has been gained.

TYPES OF PROTECTION

13.5. A nuclear power plant may be protected from the design basis flood by the following methods:

(a) *All items important to safety should be constructed above the level of the design basis flood, with account taken of wind wave effects and effects of the potential accumulation of ice and debris*. This can be accomplished, if necessary, by locating the plant at a sufficiently high elevation or by means of construction arrangements that raise the ground level at the site (the 'dry site' concept). In most States this method is preferred to the following method. The site boundary should be monitored and maintained. In particular, if any filling is necessary to raise the plant above the level of conditions for the design basis flood, it should be considered safety related and should therefore be adequately protected.

(b) *Permanent external barriers such as levees, sea walls and bulkheads should be constructed.* In this case, care should be taken that appropriate design bases (e.g. for seismic qualification where relevant) are selected for the barriers and that periodic inspections, monitoring and maintenance of the barriers are conducted. The barriers should be considered features important to safety.

13.6. For both these methods, as a redundant measure against flooding of the site, the protection of the plant against extreme hydrological phenomena should be augmented by waterproofing and by the appropriate design of all items necessary to ensure the capability to shut down the reactor and maintain it in a safe shutdown condition. All other structures, systems and components important to safety should be protected against the effects of a design basis flood which may be a lesser flood than that used for the design of the site protecting structures. Special operational procedures should be specified on the basis of the real time monitoring data on the identified causes of the flooding [6].

13.7. This approach is acceptable if the following conditions are met:

(a) A warning system should be available that is able to detect potential flooding of the site with sufficient time to complete the safe shutdown of the plant together with the implementation of adequate emergency procedures;

(b) All items important to safety (including warning systems powered by a protected off-site power supply) should be designed to withstand the flood producing conditions (e.g. wind and landslides, but excluding extremely rare combinations) that are considered characteristic of the geographical region in which the site is located.

ANALYSIS OF THE PROTECTION

13.8. The action of water on structures may be static or dynamic or there may be a combination of effects. In many cases the effects of ice and debris transported by the flood are important variables in the evaluation of pressure. Erosion by floods can also affect safety; this is discussed in a previous section.

13.9. Other factors that are related to floods should be considered in site evaluation, mainly for their potential effects on water intakes and thereby on safety related items:

- Sedimentation of the material transported by the flood, which usually occurs at the end of a flood;
- Erosion of the front water side;
- Blockage of intakes by ice;
- Biological fouling by animals (e.g. fish, jellyfish, mussels and clams)
- Salt corrosion (in the marine environment, after heavy sprays).

For design methods, see Ref. [6].

13.10. Many data have recently been recorded on in-leakage, essentially through poor sealing in structural joints or cable conduits and inspection openings. The provisions for preventing such in-leakage are mainly design related, but careful attention should be paid to the possibilities of the groundwater table rising as a consequence of a flood, human induced modifications to the territory, an earthquake or volcanism since its maximum level is a true design basis for the plant.

13.11. The two types of protection outlined above represent basic approaches for protecting a nuclear power plant from the consequences of a flood. In some cases protection can be achieved by a combination of approaches of these types. However, the interference that any work on or around the site, such as the construction outlined in paras 13.5 (a) and (b), may cause in the level of flood water at the site should be carefully analysed.

13.12. In this framework, structures for flood protection should be analysed in a manner similar to that for the other structural items important to safety.

STABILITY OF THE SHORELINE

13.13. Stability of the shoreline is an important factor in determining the acceptability of a site, in particular for sites on the shores of large bodies of water. The stability of the shoreline near the site should be investigated together with effects of the nuclear power plant on the stability.

13.14. For a river site the stability of the river channel in extremely heavy floods should be considered.

13.15. Early in the siting process the investigations should include the collection and analysis of all available historical data on the stability of the local shoreline. For sandy or silty beaches it is customary to evaluate the stability of the shoreline on the assumption of both the onshore–offshore movement and the littoral transport of beach materials. When the coast is formed by cliffs, changes may occur in the coastline over a long period and may be able to be deduced from historical maps.

13.16. Two aspects should be paid particular attention: the long term stability of the shoreline and its stability against severe storms. To investigate the latter stability, it is usually not sufficient to consider only the storm that causes the probable maximum storm surge because it may not produce the conditions critical to erosion. Storms of rather longer duration or wind fields with directions such that they cause higher waves for longer periods of times at the site are usually adopted for consideration in the analysis of the effects of erosion on the shoreline and on the structures of a nuclear power plant.

13.17. The effects of the plant structures on the littoral stability that are to be investigated include:

(a) Updrift accretion and downstream erosion as a result of blocking of the littoral drift;

(b) Beach erosion caused by interference by structures built on the swash zone of sandy beaches, with the onshore–offshore transport of material.

Analysis of shoreline stability

13.18. An analysis should be performed to determine the potential for instability of the shoreline at the site and for any possible consequences for items important to safety. Severe storms can cause significant modifications of the littoral zone, particularly to the profile of a beach. Although the long term profile of a beach in equilibrium is generally determined by its exposure to moderately strong winds, waves and tidal currents rather than by infrequent events of great magnitude, events of both types should be considered. The analysis should follow this outline:

(a) An investigation to establish the configuration of the shoreline, including its profile (e.g. berms, dunes, human made structures and immediate bathymetry).
(b) An investigation to determine the typical distributions of the grain size or composition of the beach materials in the horizontal and vertical directions.
(c) A study of tidal movements (vertical and horizontal, including sea level changes), wave exposure and climatology.
(d) An assessment of the conditions for longshore transport at the site and at the facing seabed; an evaluation of the extent of movement of sand.
(e) Establishment of the trends in shoreline migration over the short term and the long term and of the protection offered by vegetation.
(f) Determination of the direction and of the rate of onshore–offshore sediment motion, of the expected shapes of the beach profiles and the expected changes in their shapes.
(g) Evaluation of the impacts of the nuclear power plant, including the cooling water structures, on the shape of the shoreline.

Evaluation of longshore transport

13.19. The longshore transport of sand in the littoral zone should be evaluated by studying the tidal currents and the climatological data for waves as they occur in the given segment of beach, with a knowledge of how the waves interact with the shore to move sand. The following aspects should be considered to study the wave conditions near the coast; that is, the heights of waves, their periods and the directions of their propagation:

(a) Shipboard observations of the waves in the ocean area adjoining the coast;
(b) Local wind data from climatological charts of the region;
(c) Data of greater detail and reliability obtained by recording the wave conditions with wave gauges for at least one year;
(d) Wave patterns extrapolated from a similar location nearby if local data are not available.

13.20. The actual computation of the longshore transport for determining the long term stability of the shoreline and its stability under severe flood conditions requires data on the heights, periods and directions of breaking waves, which should be evaluated by means of wave refraction diagrams, and the characteristics of beach sediments.

13.21. Since the theoretical predictions are of unknown accuracy and may not be applicable to all coastlines, and since the data used to formulate the prediction usually show large experimental scatter, such theoretical calculations should be supplemented by observations and historical information on actual movements of coastlines.

SITE DRAINAGE

13.22. The plant site should be properly drained in order to prevent the flooding of safety related facilities. Flooding may occur because of:

- Intense local precipitation,
- Overtopping of the structures for site protection,
- Sheet flow on areas adjacent to safety related facilities and equipment,
- Side hill drainage running towards the plant,
- Overflowing of natural streams or human made canals in the site area,
- Ponding in the plant area due to the topography of the site area.

13.23. The drainage arrangements for the site under consideration should be made available for analysis and inspection. Guaranteeing access to the site, personnel actions at the site and the removal of the excess water should be considered a safety related system. The discharge level of the system should be chosen in such a way as to prevent flooding from affecting the functionality of the system.

TRANSPORT AND COMMUNICATION ROUTES

13.24. Operating experience highlights the general risks associated with the unavailability of transport and communication routes at the site and between the site and the surrounding areas for use in making contact with emergency teams, the turnover of operator shifts and the provision of information to the public. Such functions should be guaranteed during and after a flooding event.

13.25. The availability of communication routes external to the site during and after a flooding event involves facilities that are not always under the direct control of the site administrators. Since the availability of such communication routes is a key part of the emergency planning, a dedicated analysis of the flooding scenario should be performed together with the competent authorities as part of the hazard evaluation for the site.

14. MODIFICATION OF THE FLOOD HAZARD WITH TIME

GENERAL

14.1. The flood hazard may change over time as a result of various causes, namely:

- Changes in the physical geography of a drainage basin, including the estuaries, and changes to the offshore bathymetry, coastal profile and catchment areas;
- Changes induced by changes in climate.

Changes in physical geography

14.2. For river basins the design basis flood is, to a great extent, dependent on the physical nature of the basin. For estuaries the design basis flood can change over time as a result of changes in the geography or other changes such as the construction of storm surge barriers.

14.3. The continuing validity of the design basis flood should be checked by making periodic surveys of conditions in the basin that may be related to floods (e.g. forest fires, urbanization, changes in land use, deforestation, closure of tidal inlets, construction of dams or storm surge barriers and changes in sedimentation and erosion). These surveys of conditions in the basin should be carried out at appropriate intervals, mainly by means of aerial surveys supplemented, as necessary, with ground surveys. Special surveys should be undertaken when particularly important changes (e.g. extensive forest fires) have occurred. Where the size of the basin precludes carrying out sufficiently frequent air surveys, the use of data obtained by satellites such as Landsat should be considered.

14.4. The data obtained from flood forecasting and monitoring systems and from the operation of any warning systems should be periodically analysed for changes in the flood characteristics of drainage basins, including estuaries.

14.5. Indications of changes in the flood characteristics of drainage basins should be used to revise, as appropriate, the design flood values and to improve the protection of systems and structures, the forecasting and monitoring system, and the emergency measures.

14.6. In some coastal areas land subsidence (human induced, relating to the extraction of oil, gas and water, or natural) may have to be taken into consideration in the estimation of the apparent water height at the site, to be combined with the phenomena resulting from climatic changes.

Changes induced by climatic changes

14.7. Changes in the global climate seem to affect particularly the areas in medium latitudes. The most important consequence of the recognized effects of global warming is the need for the continuous long term monitoring of environmental parameters. The consequent updating of design data should be linked to specific procedures for the periodic updating of the hazard evaluation for the site. An accurate estimation of such effects should be carried out in the site assessment phase.

14.8. The issue of human induced climatic change will continue to be discussed around the world. The major effects with regard to the hazards to nuclear power plants are related to the following causes:

(a) Changes in temperatures of the air and the sea;
(b) Changes in the patterns, frequency and storminess of winds;
(c) Changes in the characteristics of precipitation such as higher peak levels;
(d) Changes in rises and anomalies in sea levels;
(e) Changes in the flow rates of rivers.

14.9. There are wide variations in predictions concerning human induced climatic change but some definite values should be assumed for the purposes of site evaluation for nuclear power plants. Within the framework of the Intergovernmental Panel on Climate Change investigations in relation to climate change are being carried out worldwide. The results of these investigations can be used to analyse the possible impacts on nuclear power plants. Results for the far future will have an associated unreliability. For the nuclear power plants the upper boundary of the 95% confidence interval should be taken. The period can be taken to be 100 years ahead as being the lifetime of a nuclear power plant (including decommissioning time, if needed), but it should be possible to take measures to prolong this as far as necessary. The possible changes in storminess and precipitation will be of major importance, although nothing quantitative can yet be stated on the basis of existing scientific theories.

14.10. Some safety margin should be taken into consideration in the design of a nuclear power plant. If periodic safety reviews are conducted, such a margin may refer to the interval between two consecutive reviews. If the entire plant lifetime is considered, the following generally agreed estimated variations in parameters may be considered:

- Rise in mean sea level: 35–85 cm;
- Rise in air temperature: 1.5–5 ºC;
- Rise in sea or river temperature: 3 ºC;
- Increase in wind strength: 5–10%;
- Increase in precipitation: 5–10%.

14.11. Physical and numerical modelling should be carried out in order to analyse the impacts of the climatic changes on the design basis flood in terms of:

- The increase in peak level of the discharge;
- The drop in the low discharge level;
- The increase in high wind speeds;
- The change in the dominant wind pattern;

- The increase in storm surge levels;
- The increase in size and energy of waves (because of wind speed and water depth);
- The increase in the volume of river discharges.

14.12. As concerns hazards induced by climatic change, such as rises in sea levels or gradual changes in land use, immediate actions should not necessarily be taken. In the procedure for spatial planning around the plant, land should be reserved for the adaptation of the water defences when such measures are deemed necessary. Careful monitoring should be performed to indicate when action should be taken. Such measures should usually be taken in connection with the construction of a new plant.

15. MONITORING AND WARNING FOR PLANT PROTECTION

GENERAL

15.1. When flooding proves to be a significant hazard for a plant site, continuous monitoring of the site is an essential requirement that should be performed from the siting phase until the end of the phase of plant operation for the following purposes:

- To validate the design basis flood, especially in cases for which the series of historical data are very poor.
- To support the periodic upgrading of the site hazard in the light of the periodic safety assessment (see Ref. [5]); this concern is becoming increasingly urgent as a follow-up of the consequences of global climatic change.
- To provide alarm signals for operators and emergency managers.

15.2. Monitoring and warning measures that need to be taken during plant operation will depend on the degree of protection offered by the selected site and on the type of flood protection selected for the design of the plant. Some of these measures should be implemented at an early stage of the project since they can be useful in the validation of the values of the parameters in the design basis flood.

15.3. The data to be used for long term monitoring and those to be used for a warning system should be chosen on the basis of different criteria since the purposes of monitoring and those of the warning system are not the same. The purpose of long term monitoring is the evaluation or re-evaluation of the design basis flood. The purpose of the warning system is the forecasting of an extreme event. For the warning system, special care should be taken about its ability to detect any occurrence of flooding of the plant in sufficient time to enable the plant to be brought under safe conditions. A warning system should be put in place for sites for which the flood hazard is significant for the plant design.

15.4. The warning system should be used in connection with forecasting models since the time period that would be necessary for operator actions to put the plant into a safe status may necessitate acting on the basis of extrapolations of the trends in phenomena without waiting for the actual occurrence of flooding.

15.5. In the case where the operator relies on forecasting models that are made available by organizations external to the site administration, special validation of the models and of the connection channel should be carried out in a global assessment of their availability and reliability in the event of flooding.

15.6. Specific quality assurance activities should be carried out in order to identify the competence and responsibilities for the installation of the monitoring systems, their operation, the associated data processing and the appropriate prompting of operator action.

COASTAL SITES

15.7. The following monitoring and warning networks may be considered:

- A monitoring system for basic atmospheric parameters,
- A water level gauge system,
- A tsunami warning system.

Atmospheric parameters

15.8. If the region in which the plant is located is covered by a World Meteorological Organization monitoring and warning system or by a national warning system for floods, administrative arrangements should be made to receive the warnings reliably and on time. Otherwise it should be considered whether to set up a warning system. The stations for this system should be less than 100 km apart and the frequency of observations should be no fewer than two sets of observations per day.

15.9. The regular availability of satellite imagery can provide useful information on the location and movement of hazardous atmospheric disturbances such as tropical storms. Such information should be collected to provide early warning of the approach of flooding hazards.

Inshore information

15.10. Regular tide gauging may be established for a site that is selected on a coast with a significant tide range.

Tsunami warning system

15.11. A tsunami warning system has been set up in the Pacific Ocean with its centre at Hilo in Hawaii, USA. This centre receives information on tsunamis on the Pacific coasts and disseminates the information to the States with Pacific ocean coasts. Two smaller networks have also been established for the Pacific. A proposed plant site in the Pacific region may be linked to these networks.

RIVER SITES

15.12. The following networks should be considered for river sites:

- A flood forecasting and monitoring system,
- A monitoring and warning system to be put in place on water control structures that are related to the safety of the plant.

Flood forecasting and monitoring system

15.13. If a flood forecasting and monitoring system already exists in the region, the plant should be connected to it. If there is no flood forecasting and monitoring system, a system should be set up for the collection and transmission to the plant of data on the relevant parameters, and the appropriate hydrological forecasting models should be developed. Use should be made of satellite data, satellite imagery and meteoradar imagery. The conditions of the drainage basin should be regularly monitored so that changes in land use, forest fires and urbanization of large areas can be recorded since variations in these factors may significantly change the flood characteristics of the basin.

Monitoring of water control structures

15.14. Hydrological and structural features of structures for water control should be monitored for parameters such as water levels, water velocities, sedimentation rates, infiltration rates under the structures, stresses and strains and displacements. Data for many of these parameters should be available from the operators of the structure. Warning systems between the operators of the structure and the plant operators should be set up if practicable.

15.15. When the operation of a safety related system is connected with the operation of a warning system, the operational aspects of the connection should be analysed and actions taken to ensure that the intrinsic level of safety of the safety related system is not reduced by possible unreliabilities in the warning system.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Seismic Hazards for Nuclear Power Plants, Safety Standards Series No. NS-G-3.3, IAEA, Vienna (2003).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants, Safety Standards Series, IAEA, Vienna (in preparation).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Meteorological Events in Site Evaluation for Nuclear Power Plants, Safety Standards Series No. NS-G-3.4, IAEA, Vienna (2003).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, Safety Standards Series No. NS-R-1, IAEA, Vienna (2000).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, External Events Excluding Earthquakes in the Design of Nuclear Power Plants, Safety Standards Series No. NS-G-1.5, IAEA, Vienna (2003).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants, Safety Standards Series No. NS-G-3.2, IAEA, Vienna (2002).

Annex

EXAMPLES OF POSSIBLE COMBINATIONS OF EVENTS CAUSING FLOODS

A-1. A suitable combination of flood causing events depends on the specific characteristics of the site and involves considerable engineering judgement. The following is an example of a set of combinations of events that cause floods for use in determining the design conditions for flood defence in an estuary where the following items are of importance:

- the astronomical tide,
- the storm surge,
- wave runup,
- the discharge of the river.

A-2. The design basis flood associated with an established probability of exceedance (e.g. 1×10^{-4}) for the following combination of events should be determined (including several statistical parameters, where some of them have a strong correlation and some of them have no correlation):

- High water level (which is a function of astronomical high water, storm surge (wind) and river discharge)
  plus
- Wave runup (which is a function of water level, wave height, wave period (wind) and geometry of the construction).

A-3. According to the experience in one State, this evaluation can be carried out in a conservative way, taking the maximum among the following proposed combinations, A, B, C and D:

- Combination A:

- Design water level (DWL) (given spring tide, the 1×10^{-4} storm surge value at the coast and the average value of the river discharge)
  plus, given the DWL,
- Wave runup (with the most probable wave height and wave period, and the geometry of the construction).
  (e.g. the wave parameters can be derived with a wave model using the DWL and the same wind as used for the calculation of the DWL with a hydraulic model).

- Combination B:

— High water level (HWL) (given spring tide, the 1×10^{-2} storm surge value at the coast and the 1×10^{-1} value of the river discharge)
plus given the DWL,
— Wave runup (with the most probable wave height and wave period, and the geometry of the construction)
(the probability of the coincidence of the storm surge with the river flood has been taken as 1×10^{-1}, a conservative value).

- Combination C:

— High water level (HWL) (given spring tide, the 1×10^{-1} storm surge value at the coast and the 1×10^{-2} value of the river discharge)
plus given the DWL,
— Wave runup (with the most probable wave height and wave period, and the geometry of the construction).

- Combination D:

— High water level (HWL) (given spring tide, no storm surge value at the coast and the 1×10^{-4} value of the river discharge)
plus
0.5 m freeboard.

CONTRIBUTORS TO DRAFTING AND REVIEW

Contri, P.	International Atomic Energy Agency
De Ronde, J.	National Institute for Coastal and Marine Management (RIKZ), Netherlands
Giuliani, P.	Ente Nazionale Energie Alternative, Italy
Imamura, F.	Disaster Control Research Centre of Tohoku University, Japan
Rebour, V.	Institut de protection et de sûreté nucléaire, France
Van Urk, A.	National Institute for Coastal and Marine Management, Netherlands

BODIES FOR THE ENDORSEMENT OF SAFETY STANDARDS

An asterisk (*) denotes a corresponding member. Corresponding members receive drafts for comment and other documentation but they do not generally participate in meetings.

Commission on Safety Standards

Argentina: Oliveira, A.; *Brazil*: Caubit da Silva, A.; *Canada*: Pereira, J.K.; *China*: Zhao, C.; *France*: Gauvain, J.; Lacoste, A.-C.; *Germany*: Renneberg, W.; *India*: Sukhatme, S.P.; *Japan*: Suda, N.; *Korea, Republic of*: Eun, S.; *Russian Federation*: Vishnevskiy, Yu.G.; *Spain*: Azuara, J.A.; Santoma, L.; *Sweden*: Holm, L.-E.; *Switzerland*: Schmocker, U.; *Ukraine*: Gryschenko, V.; *United Kingdom*: Pape, R.; Williams, L.G. (Chairperson); *United States of America*: Travers, W.D.; *IAEA*: Karbassioun, A. (Co-ordinator); *International Commission on Radiological Protection*: Clarke, R.H.; *OECD Nuclear Energy Agency*: Shimomura, K.

Nuclear Safety Standards Committee

Argentina: Sajaroff, P.; *Australia*: MacNab, D.; **Belarus*: Sudakou, I.; *Belgium*: Govaerts, P.; *Brazil*: Salati de Almeida, I.P.; *Bulgaria*: Gantchev, T.; *Canada*: Hawley, P.; *China*: Wang, J.; *Czech Republic*: Böhm, K.; **Egypt*: Hassib, G.; *Finland*: Reiman, L. (Chairperson); *France*: Saint Raymond, P.; *Germany*: Feige, G.; *Hungary*: Vöröss, L.; *India*: Sharma, S.K.; *Ireland*: Hone, C.; *Israel*: Hirshfeld, H.; *Italy*: del Nero, G.; *Japan*: Yamamoto, T.; *Korea, Republic of*: Lee, J.-I.; *Lithuania*: Demcenko, M.; **Mexico*: Delgado Guardado, J.L.; *Netherlands*: de Munk, P.; **Pakistan*: Hashimi, J.A.; **Peru*: Ramírez Quijada, R.; *Russian Federation*: Baklushin, R.P.; *South Africa*: Bester, P.J.; *Spain*: Mellado, I.; *Sweden*: Jende, E.; *Switzerland*: Aeberli, W.; **Thailand*: Tanipanichskul, P.; *Turkey*: Alten, S.; *United Kingdom*: Hall, A.; *United States of America*: Newberry, S.; *European Commission*: Schwartz, J.-C.; *IAEA*: Bevington, L. (Co-ordinator); *International Organization for Standardization*: Nigon, J.L.; *OECD Nuclear Energy Agency*: Hrehor, M.

Radiation Safety Standards Committee

Argentina: Rojkind, R.H.A.; *Australia*: Mason, C. (Chairperson); *Belarus*: Rydlevski, L.; *Belgium*: Smeesters, P.; *Brazil*: Amaral, E.; *Canada*: Utting, R.; *China*: Yang, H.; *Cuba*: Betancourt Hernandez, A.; *Czech Republic*: Drabova, D.; *Denmark*: Ulbak, K.; **Egypt*: Hanna, M.; *Finland*: Markkanen, M.; *France*: Piechowski, J.; *Germany*: Landfermann, H.; *Hungary*: Koblinger, L.; *India*: Sharma, D.N.; *Ireland*: McGarry, A.; *Israel*: Laichter, Y.; *Italy*: Sgrilli, E.; *Japan*: Yonehara, H.; *Korea, Republic of*: Kim, C.; **Madagascar*: Andriambololona, R.; **Mexico*: Delgado Guardado, J.L.; *Netherlands*: Zuur, C.; *Norway*: Saxebol, G.; *Peru*: Medina Gironzini, E.; *Poland*: Merta, A.; *Russian Federation*: Kutkov, V.; *Slovakia*: Jurina, V.; *South Africa*: Olivier, J.H.L.; *Spain*: Amor, I.; *Sweden*: Hofvander, P.; Moberg, L.; *Switzerland*: Pfeiffer, H.J.; **Thailand*: Pongpat, P.; *Turkey*: Buyan, A.G.; *Ukraine*: Likhtarev, I.A.; *United Kingdom*: Robinson, I.; *United States of America*: Paperiello, C.; *European Commission*: Janssens, A.; Kaiser, S.; *Food and Agriculture Organization of the United Nations*: Rigney, C.; *IAEA*: Bilbao, A.; *International Commission on Radiological Protection*: Valentin, J.; *International Labour Office*: Niu, S.; *International Organization for Standardization*: Perrin, M.; *International Radiation Protection Association*: Webb, G.; *OECD Nuclear Energy Agency*: Lazo, T.; *Pan American Health Organization*: Borras, C.; *United Nations Scientific Committee on the Effects of Atomic Radiation*: Gentner, N.; *World Health Organization*: Kheifets, L.

Transport Safety Standards Committee

Argentina: López Vietri, J.; *Australia*: Colgan, P.; **Belarus*: Zaitsev, S.; *Belgium*: Cottens, E.; *Brazil*: Bruno, N.; *Bulgaria*: Bakalova, A.; *Canada*: Viglasky, T.; *China*: Pu, Y.; **Denmark*: Hannibal, L.; **Egypt*: El-Shinawy, R.M.K.; *France*: Aguilar, J.; *Germany*: Rein, H.; *Hungary*: Sáfár, J.; *India*: Nandakumar, A.N.; *Ireland*: Duffy, J.; *Israel*: Koch, J.; *Italy*: Trivelloni, S.; *Japan*: Hamada, S.; *Korea, Republic of*: Kwon, S.-G.; *Netherlands*: Van Halem, H.; *Norway*: Hornkjøl, S.; **Peru*: Regalado Campaña, S.; *Romania*: Vieru, G.; *Russian Federation*: Ershov, V.N.; *South Africa*: Jutle, K.; *Spain*: Zamora Martin, F.; *Sweden*: Pettersson, B.G.; *Switzerland*: Knecht, B.; **Thailand*: Jerachanchai, S.; *Turkey*: Köksal, M.E.; *United Kingdom*: Young, C.N. (Chairperson); *United States of America*: Brach, W.E.; McGuire, R.; *European Commission*: Rossi, L.; *International Air Transport Association*: Abouchaar, J.; *IAEA*: Pope, R.B.; *International Civil Aviation Organization*: Rooney, K.; *International Federation of Air Line Pilots' Associations*: Tisdall, A.; *International Maritime*

Organization: Rahim, I.; *International Organization for Standardization*: Malesys, P.; *United Nations Economic Commission for Europe*: Kervella, O.; *World Nuclear Transport Institute*: Lesage, M.

Waste Safety Standards Committee

Argentina: Siraky, G.; *Australia*: Williams, G.; **Belarus*: Rozdyalovskaya, L.; *Belgium*: Baekelandt, L. (Chairperson); *Brazil*: Xavier, A.; **Bulgaria*: Simeonov, G.; *Canada*: Ferch, R.; *China*: Fan, Z.; *Cuba*: Benitez, J.; **Denmark*: Øhlenschlaeger, M.; **Egypt*: Al Adham, K.; Al Sorogi, M.; *Finland*: Rukola, E.; *France*: Averous, J.; *Germany*: von Dobschütz, P.; *Hungary*: Czoch, I.; *India*: Raj, K.; *Ireland*: Pollard, D.; *Israel*: Avraham, D.; *Italy*: Dionisi, M.; *Japan*: Irie, K.; *Korea, Republic of*: Sa, S.; **Madagascar*: Andriambololona, R.; *Mexico*: Maldonado, H.; *Netherlands*: Selling, H.; **Norway*: Sorlie, A.; *Pakistan*: Qureshi, K.; **Peru*: Gutierrez, M.; *Russian Federation*: Poluektov, P.P.; *Slovakia*: Konecny, L.; *South Africa*: Pather, T.; *Spain*: O'Donnell, P.; *Sweden*: Wingefors, S.; *Switzerland*: Zurkinden, A.; **Thailand*: Wangcharoenroong, B.; *Turkey*: Kahraman, A.; *United Kingdom*: Wilson, C.; *United States of America*: Greeves, J.; Wallo, A.; *European Commission*: Taylor, D.; Webster, S.; *IAEA*: Hioki, K. (Co-ordinator); *International Commission on Radiological Protection*: Valentin, J.; *International Organization for Standardization*: Hutson, G.; *OECD Nuclear Energy Agency*: Riotte, H.