Design of nuclear facilities other than NPPs in relation to external events

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ABSTRACT

The safety of a nuclear installation requires in general that it is sited, designed, constructed and operated to protect individuals, society and the environment against an uncontrolled release of radioactivity. External events (i.e. relevant to natural and human-induced hazard) play a major role in challenging the plant defence and therefore appropriate design provisions should be taken to guarantee an adequate safety margin in case of such events.

In recent years the development of design criteria, design methodologies and assessment approaches for the concrete implementation of the general safety principles received major emphasis for nuclear power plants, while other nuclear installations received less effort even though their radioactive inventory might be quite significant (sometimes comparable with the NPPs, like in the case of some research reactors or fuel re-processing plants), the associated risk for radiological (and chemical) contamination rather high (as in the case of the fuel re-processing plants) and their location often very close to very densely populated areas (as in the case of many research reactors, connected with universities and research centers).

There is in fact a total lack of generally accepted standards in this field and the application of general safety principles is not straightforward, sometimes giving the impression that the final safety goals are not met with the same reliability as in the power plants.

IAEA/NS addressed this issue with a series of initiatives in recent years. The most representative results have been collected in a draft IAEA TECDOC as a technical background document for a broader consensus among Member States.

This document aims at collecting the most relevant experience in Member States (MS) for the design of such facilities, providing a coherent framework where safety principles, site investigations, design procedures and safety assessment methodologies are presented in an engineering, ready-to-use context.

This paper is intended to bring to the general public the main issues that have been identified and discussed in the document, to encourage a strong feed back from the experience of Member States in a discipline where very few is published and publicly available.

INTRODUCTION

The safety of a nuclear installation requires in general that it is sited, designed, constructed and operated to protect individuals, society and the environment against an uncontrolled release of radioactivity. External events (i.e. relevant to natural and human-induced hazard) play a major role in challenging the plant defence and therefore appropriate design provisions should be taken to guarantee an adequate safety margin in case of such events.

In recent years the development of design criteria, design methodologies and assessment approaches for the concrete implementation of the general safety principles received major emphasis for nuclear power plants, while other nuclear installations received less efforts even if their radioactive inventory might be quite significant (sometimes comparable with the NPPs, like in the case of some research reactors), the associated risk for radiological (and chemical) contamination rather high (as in the case of the fuel reprocessing plants) and their location often very close to very densely populated areas (as in the case of many research reactors, connected with universities and research centres).

The design of the nuclear facilities other than NPPs was first addressed by the IAEA in 1985 with the publication of TECDOC 348 "Earthquake Resistant Design of Nuclear Facilities with Limited Radioactive Inventory" (called "document" from now on), mainly oriented to seismic siting and design. The document was widely applied in many countries and it was also considered as contractual document for some research reactors.

This publication presented simplified siting and design methods aiming at minimising sophisticated calculations and emphasised the importance of construction and detailing principles. It proposed a simplified design approach alternative to the complicated and sophisticated methodologies which are associated with and borrowed from nuclear power plant analysis and design.

Such broad use of the TECDOC in many applications in the world recently suggested a review of the original document, mainly due to the following reasons:

- Evidence from operating experience: through data bases like INES [1], the analysis of available data shows the low incidence (in terms of number of events) in the causes of nuclear events of external events (3%), compared with the mechanical failures (40%) and misoperation (44%), but it also associates external events (earthquakes, floods, extreme temperatures, lightnings, etc.) to the most challenging degradation scenarios of the defence in depth barriers.

- Feed back from applications in MS: in most cases a combination of national codes and standards for conventional or industrial facilities is applied as a design basis, often different standards for civil structures, mechanical components and equipment design, with the consequent difficulty to evaluate the safety margin of the facility.

Moreover, little emphasis is given to the safety classification and accident analysis (safety analysis reports are in fact available for very few facilities) with the consequence of a generic difficulty in the safety assessment of the facility.

- The availability of new and cheap design methodologies and computer codes. Modern design methodologies allow cheap and reliable design processes with a limited investment of time and money which leads to the requirements for a new definition of the optimal balance between design conservatism and capital investment mentioned above.
- The growing emphasis on re-qualification of existing facilities. In the case of research reactors, among 265 units in operation (2000), 50% are older than 40 years, with obvious implications in terms of ageing evaluation and re-qualification.

A first review of the document was then launched in 1998 and the following key ideas have driven the action:

1. The general safety objectives defined for power plants should be the same for any nuclear installation and therefore reference is made to the basic IAEA documents for their presentation.
2. A so called “graded approach” in hazard evaluation for nuclear installations other than NPPs is normal practice in MS and therefore should be considered: a different probabilistic threshold for definition of design basis events might be used in nuclear facilities according to their radioactive inventory (in general different than NPPs), to a different potential for dispersion in the environment and to other characteristics of the radiological risk associated to external events.
3. The investment requested for the construction and operation of a NPP is usually some order of magnitude higher than in other nuclear installations. Therefore in these latter facilities the extension of the site investigation campaigns, the use of expensive design procedures and the implementation of expensive QA systems in design, construction and maintenance should be reanalysed to provide a reasonable approach able to guarantee a plant safe operation with an acceptable investment.

A common approach to this analysis is the acceptance of a higher conservatism in all the mentioned phases, able for example to exclude some sites or to compensate, in the design phase, for the discrepancies with the real behaviour of the structures in case of external events.

Such conservatism has to be carefully evaluated in order to guarantee that the design has the required safety margin and therefore dedicated procedures have to be developed.

Some IAEA documents address the design of nuclear installations other than NPPs in relation to external events, like [2, 3, 4, 5]. However, these publications do not specify the methodology to be used in the design process, as it is done for the NPPs [6, 7, 8, 9, 10].

For the discussion in the next sections, the following nuclear facilities have been identified:

1. Uranium mines, mill factories and uranium tail repositories
2. Fuel conversion plants
3. Enrichment plants
4. Fuel fabrication plants (including MOX fuel facilities)
5. Research reactors
6. Radio isotope laboratories
7. Independent spent fuel storage facilities
8. Fuel reprocessing plants
9. Near surface repositories for low and intermediate level waste
10. Deep waste disposal for permanent storage
11. Heavy water distillation plants
12. Accelerators

However some of them have been excluded from the document, because of atypical layout and configuration, peculiar safety objectives or military installations. The resulting set of facilities addressed in this document are in the following identified as NFOP (Nuclear Facilities Other than NPPs).

In any selected facility, some special equipment may be hosted which cannot be designed according to the general principles stated in this document because of their peculiar functions or their atypical configuration. The reactor core in research reactors, the centrifuges in the fuel enrichment plants are two typical examples. Appropriate, specific design codes should be used in these cases.

Other critical tasks like material capacity evaluation, geotechnical assessment, QA, monitoring, etc are not addressed in this document. The document is focused on the evaluation of internal forces in the structural members, starting from the siting process, which is usually the most expensive segment of the whole design process.

For activities not covered in the document, the designer is recommended to follow either conventional standards or nuclear standards, according to the risk classification of the facility of interest.

In the following, the main sections of the revised draft IAEA TECDOC are presented in a critical way: they represent an attempt to reach a consensus on crucial technical issues in view of a global approach to safety of NFOPs. In its final version a larger compatibility with revised versions of Safety Guides will also be reached.

SAFETY OBJECTIVES AND CLASSIFICATION

Safety objectives

As defined in [11], the safety objectives stated for NPPs should be applied also to NFOPs.

The **general safety objective** stated for all nuclear installations is to protect individuals, society and the environment from harm by establishing and maintaining in nuclear installation effective defences against radiological hazards. This general nuclear safety objective is supported by two complementary safety objectives dealing with radiation protection and technical aspects.

The **radiation protection objective** is to ensure that in all operational states radiation exposure within the installation or due to any planned release of radioactive material from the installation is to be kept below prescribed limits and as low as reasonably achievable, and to ensure mitigation of the radiological consequences of any accident.

The **technical safety objective** is to take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences should they occur: to ensure with a high level of confidence that for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor and below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low.

Safety classification of the facilities

To achieve the above mentioned safety objectives in case of an external event (EE), the design of the facility should prevent any damage to structures and equipment that could lead to significant exposures to facility personnel or members of the public because of uncontrolled release of radioactivity.

As a preliminary screening criteria on the NFOPs to be considered as facilities with associated radiological risk (in case of EEs), it can be assumed that a conservative estimated amount of the radioactive inventory is released following an accident (induced by an EE). In this case the radiological limits for workers and public should not be exceeded.

The consequences to workers and public are discussed in the Safety Standard on International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series 115-I.

In case the screening shows that the radioactive inventory of the facility is “not significant” (i.e. the criterion for the limit to the public is met), conventional standard for the design of the facility can be applied, according to the national codes for industrial facilities (of course a parallel evaluation should be carried out for the other risks, like chemical, fire, etc.). In case the limits for workers are exceeded, local engineering provisions should be put in place, but without affecting the design of the whole facility.

If the radioactive inventory is “significant”, an evaluation of the risk associated to the facility should be carried out to define an appropriate safety margin to be associated to the design for EEs where risk is defined as the product of the probability of the initiating event (external) and a measure of the consequence generated by a radiological dispersion.

The probability of any external event at the site should be evaluated according to its site specific hazard: detailed recommendations are provided in the document for the most relevant EEs.

The probability that EE generate a radiological consequence depends on many characteristics both of the source (facility) and of the events, such as:

- Amount, type and status of radioactive inventory at the site
- Intrinsic reliability and hazard associated to the chemical and physical processes which take place in the facility - Installed thermal power in the facility
- Configuration of the facility for different kinds of productions
- Facilities designed for experiments and research (such activities have an associated intrinsic unpredictability)
- Need for active safety systems to cope with mitigation of postulated accidents
- Characteristics of the event (e.g. wind and explosion have a high potential for dispersion, while earthquake and aircraft crash have a minor contribution on the dispersion)
- Environmental characteristics of the site relevant to dispersion (e.g.: windy area, sea site, etc.)
- Potential for long term effect in case of contamination (long lived radionuclides, persistent effect in the environment)
- Number of people potentially affected by an accident at the facility

Such criteria should be used in the classification of the risk associated to the facility, ranging from a minimum risk (residential building) to the higher values (nuclear power plants).

However, the classification of NFOPs in relation to their risk is in general difficult because of the large variety of designs, the wide range of power levels, the different modes of operation and purposes of utilisation, the particularities of the site, and differences among operating organisations at the facility.

For some facilities the application of the whole procedure for facility classification as described above shows a strong correlation between risk associated with the facility and its installed power or radioactive inventory, instead of all the criteria described above. This correlation might simplify the classification process at the beginning of the design. Of course such assumptions should then be assessed in the safety assessment phase and justified in the SAR.

In general, research reactors with powers of several tens of megawatts, fast neutron spectrum reactors or small prototype power reactors are classified as nuclear power plants and they are beyond the scope of the revised TECDOC.

Fuel reprocessing plants are usually classified in the highest class of risk, but the engineering features are very different from NPPs and therefore they are included in current discussion.

The classification of the facility has influence on the following tasks through a decisional process which is not unified among the Member States:

- Selection of the annual exceedance probability for any EE at the site. This concept is interpreted in the TECDOC through a conservative evaluation of the site hazard
- Definition of the safety margins in the design or, in general, of the reliability levels which such functions should comply with.
- Number of safety features: number and quality of defence in depth barriers and levels, emergency systems, emergency procedures, etc. (in this case, also engineering tradition, construction practice, economic consideration have strong influence). In particular the safety classification of systems and items (including their acceptance criteria in case of an EE) is a very important task affected by the facility classification.
- Adoption of different QA level in siting, design, construction and operation

As a result of a survey of the main facilities in the scope of the TECDOC, aimed at the identification of the most common safety requirements for such facilities, the most recurrent accident scenarios in NFOPs were identified as in the following:

- Criticality
- Fire and explosions
- Internal misoperation with radioactive material spreading on-site and off-site

This data should be used for the safety classification of NFOPs and their components.

Classification of items in relation to EEs

According to the basic survey carried out on the most significant facilities, it comes out that the the most common structural requirements can be summarised as follows:

- Confinement or isolation (ventilation systems): leaktightness
- Leaktightness of pools
- Drop loads
- Functionality of safety related items
- Appropriate anchoring of items
- Interaction problems: mechanical, chemical or through impairment of operator action
- Shielding

Following the general criteria defined above for the classification of the facilities according to their risk, the safety analysis of the plant should assess number and characteristics of the safety systems (including the barriers to prevent radiological accidents) through analysis of the consequences of any postulated initiating event (including EEs) with application of the “single failure” criterion to any safety group (see [11] for definitions). Special limitations to redundancy and diversity may be considered for passive systems, as specified in [11].

The safety analysis should be mainly based on the application of the defence in depth, aimed at maintaining the effectiveness of the physical barriers placed between radioactive materials and workers, the public and the environment.

The design of systems and components in relation to EEs requires a classification with the following aims:

1. the identification of items and systems important to safety (i.e. items needed to perform all actions required for the postulated initiating events to ensure that the radiological limits are not exceeded, even in case of degeneration into a plant accident. Items which would lead to radiation exposure to workers or public in case of failure should be added to such category). These items have to be protected in case of an EE.

2. the identification of the safety functions assigned to them, and therefore their acceptance criteria (e.g. integrity, stability, operability, etc.). The design has to meet such acceptance criteria.

For a rational basis in the design, such information should be organised through an External Event Classification (EEC) process of all plant items in order to identify the items who need to be considered in case of any EE and the relevant requirements. To this aim, three classes can be identified:

- **External Event Class 1:** safety systems pertaining to EE safety groups [11] or safety systems which, during and after an EE, interact with items in the safety group of the EEs
- **External Event Class 2:** safety systems which are not in the EE safety groups and which, during and after an EE, don't interact with EEC1 items.
- **External Event Class 3:** items not important to safety which could impair proper functions of EEC1 and EEC2 items or the operator action.

Acceptance criteria should be stated for both the operational state of the facilities and the accident conditions considered in the design of the facility. Such criteria vary among Member States: they may include considerations such as those listed below.

a) Radiological criteria, such as:

- ALARA levels
- Dose limits (or targets) for facility staff and workers at the facility site and the general public;
- Release limits to the environment; and
- Risk criteria (where applicable)

b) Performance criteria, including

- Limits to damage of the first physical barrier
- Limits to damage of safety significant structures, systems and components
- Frequency limits for certain anticipated operational occurrences and for particular accident conditions, including frequency limits for significant damage of physical barrier (where applicable).

These criteria should define relevant behaviour limits for any component and structure in any EE class above according to the safety function which is associated to them in case of a sequence where an external event is the PIE.

It turns out that the EE classification is not related to the kind of behaviour limit (acceptance criteria) associated to the component/structure, but it is related only to the amount of safety margin requested (Fig.1). The more relevant a component is for safety, the highest safety margin has to be considered in its design. This safety margin is intended in general sense as it might include design safety margins, but also reliability evaluations, number of safety features, QA prescriptions etc., as described above.

Fig. 1 Interaction between item classification and acceptability limits

Moreover, the EE classification does not have any influence in the application of a specific methodology for the numerical simulation, as it was in the past: numerical simulation techniques have to be validated in terms of their simplified assumptions and therefore in terms of their conservatism. This approach is more in line with the availability of sophisticated calculation techniques which can be applied to the design of NFOPs without sensitive additional costs to the process.

According to the proposed approach, an interaction could be stated between the facility classification and the item classification, particularly when the mechanism to control the safety margin is left to the reduction of the internal forces only, as in a “single parameter control”. In this case a Design class can be established according to the demand requirements, which is associated to a specific factor for internal forces. Within each Design Class there is the potential for one or more Acceptance Criteria to be used. Table 1 shows a proposal for such interaction.

Table 1. Relationship between facility classification and items classification in case of “single parameter control”

DESIGN CLASS SELECTION				
Hazard Category	High 1	Moderate 2	Low 3	Conventional 4
EE Class				
EE Class 1	Design Class 1	Design Class 2	Design Class 3	Design Class 4
EE Class 2	Design Class 2	Design Class 3	Design Class 3	Design Class 4
EE Class 3	Design Class 4	Design Class 4	Design Class 4	Design Class 4

Safety margin

In order to meet the safety requirements discussed above and to allow simplified and well consolidated design procedures, it is common practice to apply conventional standards for structural design and for the qualification of components and equipment in NFOPs, leaving to the peculiar hazard definition procedures the role of carrying the safety margin correspondent to the risk classification of the facility. Therefore the approach in the design can follow a simplified sequence: the hazard is defined in a conservative way according to the facility classification. Then internal forces are reduced according to the item classification, in a graded way as suggested in table 1, from “no reduction” up to the building code and standards for conventional buildings. In general such reduction has the form of a factor applied to internal forces, but in some cases it has also a physical meaning such as the ductility in the seismic design.

A general approach is shown for NPP design in Fig.2 for comparison, where the contributions to the safety margin are highlighted.

Fig. 2 Steps in the design process where safety margin might be located

An other conservative margin is usually applied to the hazard evaluation to compensate for simplified investigation campaigns or for simplified calculation methodologies. Such conservatism should be demonstrated by the designer and it should never overlap with the safety margin requested by the classification discussed above, but added on top of it.

In conclusion, in this design approach load combinations and material properties could be taken by standard design procedures and the whole siting/design process has only two major modifications compared to conventional building design:

- the hazard and the site properties are required to be site specific (or at least to include the effect of the risk classification of the facility). The internal forces should be corrected by a “pseudo-ductility” coefficient according to the interaction of facility and item classification, as shown in table 1
- the assessment of the acceptance criteria (and therefore the design limits associated to the material capacities) should be carried out explicitly in compliance with the safety objectives and documented in the SAR.

As a consequence, the following tasks have to be detailed in the design of NFOPs:

1. the site exclusion criteria should be revised (i.e.: in case of EE which require specific, complicated and expensive protection structures and systems, it might be convenient to exclude the site) and typical layout characteristics of NFOPs should be considered in the safety analysis, aiming at a simplification of the design basis for the facility
2. a requirement on the minimum level of site investigation should be defined and rules have to be defined to compensate for the limited investigation campaigns and to guarantee a certain conservatism;
3. an evaluation should be carried out concerning the safety margin to be embedded in the derivation of design basis from the site hazard, correspondent to the risk associated to the facility (i.e. its classification)

Concerning item 1, the evaluation of the site hazard for external events can in general follow the IAEA recommendations for siting and design of NPPs and research reactors [5, 6]. However, the site selection process can consider more restrictive exclusion criteria than for NPPs and research reactor, as a compromise with the investment requested for the facility construction and operation. In this sense, some events which are difficult or expensive to protect the facility from could be screened out, like aircraft crash (thick shielding and special equipment qualification would be required to facilities often without a containment), explosions (blast resisting structures are required), flooding (site protection engineering structures should be built and maintained), etc. In fact in NFOPs usually the internal accident scenarios do not imply high demand to the structures, like in the case of NPPs where, for example, a containment is normally part of the layout. Therefore a protection to external events would add heavy requirements to the design which might be incompatible with a rational approach.

In other cases an exclusion of some events from the design basis can be done according to specific engineering provisions implemented in NFOPs. An example is the consideration in the safety analysis of the typical spreaded building layout which might reduce the consequences of an aircraft crash.

As a consequence, when NFOPs are at the same site of a NPP, they share the same hazard, but the design basis might be different due to the considerations above.

Examples of such approach are presented in the next sections in the case of earthquakes (conservative definition of the hazard for safety reasons and for reduced investigations) and geotechnical investigations (conservative evaluation of design data as a consequence of reduced investigation campaigns) respectively.

SIMPLIFIED DESIGN BASIS

An example of the procedure outlined above is provided in the following for the case of the earthquake which usually represents the most common natural hazard for NFOPs.

Based on availability of instrumental or historical data, one of the following methods may be used to define design basis ground motions. In any case, the minimum design level acceleration should be 0.1 g.

Site specific Design Response Spectra based on instrumental data

In case some instrumental data, such that the location of seismogenic sources and zones, attenuation relationships and possibly hazard maps within the region, are available for the region, then a site specific design response spectra (including site effects) can be generated by either using the envelope of response spectra (for 5 % damping) calculated from recorded data or using hazards maps that are constructed using such data. The Safety Guide for NPP siting [6] should be used in this case, particularly in the evaluation of sufficiency and reliability of available data, with the implicit assumption of the safety margin typically embedded in the hazard evaluation for NPPs. Appropriate simplifications approved by the Regulatory Bodies might lead to a reduction of the embedded safety margin according to the facility classification.

Design Response Spectra Based on Historical Seismicity

In the event that requisite instrumental data is not available, the Design Basis Ground Motion should be evaluated on the basis of the maximum historical intensity. For this evaluation, the following procedure might be applied, provided the site region shows a reasonable uniformity from the seismotectonic point of view:

- A zone having a radius of minimum 100 kilometres from the site. Larger radius of up to 200 km should be considered when data is lacking and there is low seismicity.
- Using available publications and catalogues the maximum observed intensity in this area should be established and assumed at the site. The information should cover as much historical data as possible. In any case it should be extended to at least 100 years [6].

To each seismic design level index, a minimum value of design free-field acceleration for firm bearing strata (A_b) should be assigned as shown in Table 2. These assigned values should be compatible with the seismic provisions of several national building design codes currently adopted by several countries. However, intermediate design accelerations can be assigned based on detailed analyses of the data and other considerations.

Table 2. Assigned Minimum Free-Field Design Accelerations.

Range of Maximum Historical Intensity, I_{max}^{*1}	Seismic Design Level Index	Assigned Design Acceleration for Firm Bearing Strata A_b (g)
$I_{max} < VIII$	1	0.1
$VIII \leq I_{max} < IX$	2	0.2
$IX \leq I_{max}$	3	0.4 ^{*2}

¹ Modified Mercalli Intensity Scale

^{*2} For Seismic Design Level Index 3, intermediate design accelerations can be assigned between 0.2~0.4 based on detailed analyses of the data and other considerations

The conservatism of such evaluation is embedded in the assumption of a large area of investigation, much larger than in the case of NPP siting: the reduced investigation campaign is then compensated by an enlargement of the area of interest and therefore in the use of the highest seismicity values of the whole area for the site.

Design Response Spectral Shapes

In the absence of site-specific design response spectra constructed from instrumental or historical data, Figures 3 and 4 can be used as the normalized design response spectra representing different design intensity levels and soil types.

Fig. 3 Normalized Design Response Spectra for Seismic Design Level, Indexes 1 and 2.

Fig. 4 Normalised Design Response Spectra for Design Level 3.

These spectral shapes are given for a 5% damping ratio and are valid as horizontal components. In order to get the spectral shape for other damping ratio ζ , the value of acceleration for at points B and C have to be multiplied by the D_d coefficient defined as: $D_d = 1.5 / (1.0 + 10 \cdot \zeta)$ for $2\% < \zeta < 20\%$.

Both horizontal components of earthquake will be taken equal to the above defined spectrum.-

The vertical component of accelerations should be accepted to be at least 50 % of the horizontal. component.

SITE INVESTIGATIONS

As in the previous chapters, an example is provided for limited site investigation campaigns for the case of geotechnical data.

Geological and geotechnical investigations at the site should be performed with the following objectives:

1. the assessment of possible geological/geotechnical problems involving surface rupture due to faulting, liquefaction, collapse and slope instability as a consequence of an earthquake.
2. the evaluation of the soil characteristics so that reasonable soil characterisation can be achieved in the modelling of soil structure interaction, mainly in seismic analysis. For this, it is necessary to determine depth to bedrock, shear-wave velocity variation and average shear wave velocity for a depth of 25 m.
3. the evaluation of geotechnical parameters to be used in the design of the foundation for static and dynamic loads.

In case of a shear wave travelling in the ground, the dynamic amplification effect of geological formations overlying the firm bearing strata is considered in terms of the soil factor, γ , as follows:

$$a_g = \gamma A_b$$

where a_g is the design ground acceleration and the value of soil factor, γ , is given in terms of soil characterization as indicated in Table 3. It should be noted that soft to very soft soils and fill ground are not included in this table. Furthermore, the larger soil factor for Soil Type 3 can be used only when justified by investigations.

The amount of geotechnical investigations to be performed should be based on the extent of potential problems, the available data and physical size of the facility. It is recommended that the soil profile is physically identified (i.e. through drilling) to a depth equal to at least one half of the maximum foundation dimension but not less than 25 m. The depth to firm bearing strata should also be determined using geological inference, boreholes or geophysical methods. The geotechnical investigations should include determination of the bearing capacity, shear-wave velocity representative of the site and other soil parameters for foundation and building design. These will primarily involve borehole drillings in sufficient number and to

sufficient depth, depending on the soil conditions, but at least one below every safety related building. For competent rock sites where the rock formation continues to a sufficient depth, drilling may not be necessary.

Table 3. Soil Characterization.

Characterization	SOIL TYPE		
	1	2	3
DESCRIPTION	Firm Bearing Strata (thickness > 25 m)	Other soil than those defined as 1 & 3, or with lower thickness	Alluvium ground which is thicker than 25m
Shear-Wave Velocity V_s (m/sec)	>700 m/s	300-700 m/s	150-300 m/s
Soil Factor, γ	1.0	1.0-1.5	1.5-2.0 ^{*1}

*1 Based on detailed analyses of geotechnical data and other considerations, Soil Factor less than 2.0 can be used.

In parallel with the foundation investigations and the use of available geological / geotechnical data, studies should be performed at the site to assess possible hazards resulting in permanent soil deformations (including surface rupture, liquefaction, collapse, slope instability). In the event that there are special features of the site such as unusual surface and subsurface topography, then investigations should be carried out to determine if there will be focusing of incoming seismic waves.

SEISMIC DESIGN OF BUILDINGS

Generalities

The design of structures must lead to simple general shapes and as much as possible regularity in plan and elevation. Structural detailing must avoid brittle parts and should follow requirements of the national seismic building codes. Pre-cast panels (or other elements) should be connected such that they behave as an integral unit during an earthquake.

It is recommended that the foundation elements for structures important to safety be located at the same elevation. A common foundation raft is recommended. Structures should be designed to resist the overturning and uplift effects caused by the earthquake forces specified with due consideration of gravity forces and buoyancy. It should be noted that potential problems are mainly related to foundation behaviour and soil bearing capacity.

The minimum requirements imposed to structures, during and after an earthquake, are:

- **For Class I structures**, full functionality, such as leak-tightness, is required. This often implies an elastic behaviour in the event of the Design Basis Earthquake.
- **For Class II structures**, capacity of supporting safety related components, equipment and systems should be maintained. This often requires limited inelastic deformation and is guaranteed by lower ductility coefficients than for Category III structures in the event of the earthquake.
- **For Class III structures**, non-collapse which allows displacement controlled inelastic behaviour is required. This may be achieved using lower ductility coefficients comparable with conventional seismic code (national code)

The use of ductility coefficients is associated with careful application of special detailing provisions defined in the national seismic codes. National building codes or standards for materials such as concrete and steel generally specify an increase in allowable stresses for extreme loads such as earthquakes. These increased values may be used as the elastic limits for the earthquake resistant design of Category I, II and Category III structures.

If such an increase is not specified in the national codes or standards, then an increase of 33% may be taken in the allowable stresses of the permanent load for concrete (compressive and shear), structural steel (tensile, compressive and shear) as well as foundation soil (bearing capacity). However, applied buckling loads should not exceed 0.75 the critical buckling load. Alternatively, if load factor and strength design procedures are used, the overall load factor may be taken as 1.25.

Concerning the numerical procedure to be used in seismic design, two methods are recommended: the stick model with modal spectral analysis and the simplified dynamic analysis. However, when applying the simplified dynamic approach, the structures in categories I and II are desirable to have uniform mass and stiffness distribution.

Other methods such as the equivalent static approach, as described in the former version of the TECDOC, or two dimensional finite element methods using time-history analyses may be used provided that the results are deemed to be reasonably conservative as compared to other approaches.

Soil Structure Interaction

In general the dynamic response of the structure should be calculated taking into account the radiation of energy of the waves propagating into the soil region not included in the numerical model of the superstructure. For the structures deemed to be affected by soil-structure interaction (SSI) phenomena because of their stiffness compared to the soil one, analyses should include SSI procedures.

In a soil-structure interaction analysis, it is computationally more efficient to use the substructure method. In this method, the unbounded soil is analysed first, as a dynamic system. In the second step, the structural response supported on this spring-dashpot system is computed. Formulas for the numerical evaluation of stiffness of the spring and the damping values to be assigned to a soil spring-dashpot system applied at the base of the structure model are available in literature.

Considering the flexibility of the soil makes it rather difficult to determine an exact response of structures. Varying the important parameters such as the soil properties should lead to response predictions which will consequently result in a safe design. In the analysis, it is recommended to take into account the uncertainty on soil modulus by considering 3 cases : G, defined from Vs in Section 3, $2/3G$ and $4/3G$. The design configuration of structural elements should be determined to envelope all of the calculated results obtained using the above design response spectra. In case of very irregular subsoil conditions, the variation should be increased. In case of important stratification with a soft upper layer, radiation damping should be decreased.

CONCLUSIONS

The main issues involved in the review of TECDOC348 have been presented with two examples related to earthquake design and geotechnical investigations. major effort has been spent in the interpretation of the general safety objectives and therefore in the definition of design rules which guarantee a graded approach for the NFOPs.

The IAEA secretariat hopes that the revision of the TECDOC is a major chance for the international community to assess common rules for the design of NFOPs according to general safety criteria accepted for nuclear power plants.

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