Abstract

This paper briefly reviews the principles involved in the planning and design of the proposed facility to cater for seismic and structural loads. The conceptual layout is discussed, as well as the different load characteristics and scenarios. An outline is given of a model used to estimate the seismic loads, whereafter the different analytical models are discussed.

1. Background

This paper briefly reviews the structural and seismic design of the proposed facility. The structure serves the main role in supporting the sensitive equipment, protecting it from the external environment, internal and external missiles, and providing some rudimentary protection against the sudden uncontrolled release of radio-active material. The building will need to be designed to provide the necessary protection, but also be adaptable to different environments and circumstances. The current prototype is being planned for the Koeberg site in the Western Cape (close to Cape Town), but the ultimate goal is to be able to place such facilities at virtually any location in the world. In designing this prototype, the objective has therefore been set to ensure that it can be 'transported' to a wide range of sites: of particular interest is the seismic input parameters.

The paper reviews the forces and conditions to which the building will be subjected. The principles involved in planning the layout of the building are reviewed. Next the fundamental issues involved in estimating the seismic input parameters are reviewed, as well as the principles to be used in performing the seismic analyses.

2. Design considerations

The concrete structure that will house the proposed system is being planned to fulfil a multiple range of functions. The different input requirements are outlined below.

2.1 Structural Requirements

2.1.1 Strength

The structure will be expected to fulfil the normal operating loads, as well as a number of critical (accident) conditions. Normal loads to be considered would include the following:

- the support of heavy equipment
- slight under or over pressures during operational conditions
• construction loads (e.g. installation of the process equipment, etc)
• normal heat loads during operational conditions

During accident conditions, it is anticipated that the following conditions would have to be catered for:
• protecting the process equipment from missiles, both internally generated (e.g. turbine blades, broken pipes, etc) and external missiles (e.g. aircraft)
• the protection against slight over-pressures during a potential accident, and
• provide sufficient strength against seismic loads during earthquakes.

2.1.2 Stiffness

The sensitive nature of the equipment calls for a relatively stiff supporting structure to prevent relative movements between support points of the equipment. A key design parameter in planning the layout of the building has therefore been to ensure that the building does not exhibit excessive relative displacements during dynamic loads, and that piping and equipment are not subjected to large differential movements of its supports. Research has shown that such relative displacements could seriously jeopardise the structural integrity of the process equipment. Furthermore, resonance between the different modes of the equipment and the building structure should be prevented, as this could seriously jeopardise the safety of these critical equipment.

However, the supporting soil of the site could furthermore impact on the dynamic loads experienced by the building. Experience and extensive research have shown that substantial amplification of the seismic motions can be expected in the case where the facility is situated on soft soil deposits. Care should therefore be taken to ensure that such amplification does not occur. Special care would be required where such situations do occur: it is usually advisable to prevent resonance between building and the supporting soils.

2.2 Integrity

The second key objective of the building will be to ensure sufficient protection of the process equipment from the natural external environment. This entails the protections against the external corrosive sea air, as well as the potential damaging effect of the ground water.

The prior matter will be addressed easily through high quality concrete construction. Similarly, the structure will be designed to withstand at least the minimum over pressure that could be expected during the initial phases of a possible blow-down of the system: special pressure release gates will be provided to release any potential over-pressure as soon as possible. It is therefore not anticipated that the structure will tested for leak tightness, and not special effort will be put into creating an absolutely leak-tight environment.

The prototype plant will be situated on the Koeberg site, where the sand cover over the underlying rock is approximately 20m thick. The water table is also quite high, being right
next to the sea. It can therefore be expected that substantial water proofing will have to be provided. A cavity wall system is currently being investigated for this purpose.

2.3 Structural Layout

The primary structure is planned to consist of a number of heavy concrete walls and floor required to support the process equipment (see Figure 1). The large latter force will be resisted by the internal floors, while a vertical load carrying system is being devised to provide for the support of the vessel, the heavy overhead crane, the numerous large pressurised gas containers, and the roof itself. Special care will be given to finding a solution which takes into account the dynamic response of the roof during seismic events.

![Figure 1: Conceptual Layout of Building](image)

A key role to be played by the structure is the protection against external missiles. It will be designed to withstand the following two cases:

- Cessna 172 (which would not be allowed to penetrate the external wall), and
- Phantom F1, (which would not be allowed to penetrate the protective boundary surrounding the process equipment.

This protective boundary is illustrated in Figure 2.

![Figure 2: Protective Boundary Above Process Equipment](image)
3. Seismic Design

3.1 Seismic Input Parameters

3.1.1 Properties of earthquake

Effects of Earthquakes

Earthquakes represent some of nature's most catastrophic events which could wreak havoc in any community. Fortunately, the South African region is known for its seismic stability, and only a relatively small number of earthquakes occur. However, earthquakes do induce significant forces in buildings and other structures, and extensive damage could occur in buildings if the necessary precautions are not taken. It is therefore necessary to take cognisance of these effects during the design stage.

An earthquake is manifested by a sudden, random, rapid movement of the ground which could have a duration of between 2 to 20 seconds. A typical recording of the ground motion in the three directions are uncorrelated. The maximum horizontal acceleration measured during an event can reach 1 or 2g (where g is the gravitational acceleration of 9.81 m/s\(^2\)) but in most cases it is less than 0.5g. In frequency terms, the dominant frequency of the motion generally lies in the range of 2 to 20 Hz (i.e., the ground vibrates at frequencies of between 2 and 20 Hz).

Classification of Earthquakes

Various scales are used to measure the degree of intensity of an earthquake. The two more commonly used scales are the Richer magnitude scale, and the Modified Mercalli Intensity scale. The Richter scale is used most commonly where sufficient instrumentation is available to measure the motion of the earth. This scale is an open-ended scale, and larger events can reach 8.5 on this scale. The largest event recorded to date in Southern African is the main shock of 29 September 1969 at Ceres, which registered 6.3 on the Richter scale. The Modified Mercalli Intensity scale is generally used in cases where no instrumentation recorded the event, and where local evidence needs to be used to estimate the severity of the event. The earthquake at Ceres was assigned an MMI value of 9, being the largest recorded in this region.

Earthquakes are induced by a range of different mechanisms in the upper layers of the earth crust. The major cause of earthquakes is the sudden release of energy when two adjacent sections of the crust move with respect to each other. Such movement typically occurs at the interplate boundaries of the earth. This results in a concentration of earthquake epicentres along the American coastal belts, in the Philippines, and in some parts of the Mediterranean. Other causes include volcanism, and other effects which could cause stress concentrations in the rock layers, such as an increase in load on the earth crust due to the construction of dam, or the seasonal accumulation of water in some swamp areas. However, these situations generally result in relatively small seismic events.
Effect of Distance

The epicentres of larger natural earthquakes are located at depths of between 25 and 40 km below the surface. From there the energy is transferred as P (compressional), S (shear) and Raleigh waves through the earth to areas further away. The intensity of the observed ground motion (and therefore the MMI observed at a particular position) attenuates with distance from the epicentre. Although not strictly correct, this attenuation of intensity can be represented by a logarithmic function expressed as:

\[ \log I = \log I_o + a \log R + c \]

where \( I_o \) is the intensity at the epicentre,

\[ I \] is the intensity at distance \( R \), and

\( a \) and \( c \) are constants.

Therefore, sites further afield from seismically active zones are affected less significantly than those close by.

3.1.2 Seismicity in Southern Africa

Earthquakes have been recorded in the Southern African region since as early as 1620, but a scientific record of events has only been kept for the past 20 or 30 years (Fernandez 1970 - 1986). Largely due to a lack of data, seismologists have not been able to construct a clear model of seismic activity in this country, and quite large error bounds are therefore by necessity included in any codified guidelines. It can be expected that this may also be the case in a number of other countries where these plants may in future be situated. A brief outline of the methodologies used here is given to illustrate that the lack of seismic information should not preclude the development of some model of seismic behaviour of the region.

![Figure 3: Points of Interest and Seismically Active Areas](image-url)
From the available data it is clear that there seems to be higher concentration of earthquakes in the Cape Town - Ceres area, where some of the larger events took place (see Figure 3). A number of larger earthquakes have also occurred in the Zululand area, as well as in Lesotho and in Koffiefontein. A larger number of earthquakes (albeit small) occur in the northern region of Botswana, and in the vicinity of new large dams, such as the Kariba dam. This data was used to develop the seismic hazard map used in the design codes. Alternatively a probabilistic approach could be used to develop design spectra (Wium and Opperman, 1986).

A large concentration of earthquakes are also found in the major active gold mining areas of Transvaal and the Orange Free State. The epicentres of these events are typically located at depths of between 2 and 3 km, and they generally have quite short duration. Due to their very shallow epicentres, they tend to attenuate very rapidly, resulting in only limited impact on constructed facilities.

### 3.2 Seismic Design Parameters

This section briefly summarises the methods used to develop the seismic risk model. The methodology used in this work is based on the work of Cornell (1968), and on later extensions implemented by Anderson and Trifunac (1978) and Lee and Trifunac (1985). Two numerical models were developed to represent the unique properties of the Southern African region. The various aspects involved in this procedure are briefly discussed below.

#### 3.2.1 Seismicity

The occurrence of earthquakes in a given region can be represented by a model of the seismicity which describes the location of seismic events in the region, the frequency of these events, and their magnitude or intensity at the epicentre. Typically, the region can be divided into a number of different seismic zones or features with which earthquakes can be associated. The most obvious features are faults and point sources, but in many cases, earthquakes cannot be associated with any particular feature, and a region therefore has to be treated as an area of distributed seismic activity. It is assumed that throughout each of these zones, there is an equal probability of an earthquake of a specific intensity or magnitude occurring anywhere in such a zone.

This model is expressed in terms of the Modified Mercalli Intensity (MMI) at the epicentre. Although a model of magnitudes would be more apt, little or incomplete magnitude data exists on earthquakes in Southern Africa prior to the 1970’s. Seismologists therefore have to rely on records of MMI values.

The Seismological Data Bank (consisting of a comprehensive list of all recorded earthquakes in Southern Africa from 1620 up to 1983) was obtained from the Geological Survey of the Department of Mineral and Energy Affairs (Fernandez, 1985). All events after 1900 were selectively grouped into seven seismic zones, and only those events subsequent to the turn of the century were retained. Fore- and after-shocks were judiciously excluded from the list of earthquake.
However, a close inspection of the cumulative energy of the earthquakes shows that the available data on the seismic history of Southern Africa is not complete. Had this been the case, the average trend of the cumulative energy would have been constant for the full period from 1900. This certainly is not the case. Instead, in many regions this data is only complete from the early to late nineteen fifties. This data can hardly be used to correctly estimate the seismicity in a region.

On the other hand, it would seem as though the record of seismic events is not complete for the smaller events that occurred prior to the fifties, and that the list becomes progressively more complete in the smaller events as the time goes on. For instance, it seems that in some areas all large events (those with an intensity greater than or equal to 8) may be complete from as early as 1652, being the period for which written records are available. These events are so large that they would have been recorded by the public had they occurred. On the other hand, smaller events (with intensities between 5 and 7) may be complete from approximately 1900, while smaller events only seem to be complete from 1950 or even later.

It was therefore decided that all available data be used to compile a more representative model of the seismicity of each region. This can be done by establishing the average rate of events of a particular intensity during that period for which the events of that intensity is complete, and by extrapolating these events over a longer period. It is suggested that the longest available period be used as the basis for calculating the seismicity: in this case, it would be for the period from 1652 to 1983, being the period during which the Southern Cape has been populated on a continuous basis. The number of events that occurred during a shorter period should therefore be extrapolated to cover this full period.

All that remains to be done is to select that period for which the data of each intensity is complete. It was therefore decided that this can be regarded as that period during which the moving average of the annual number of events remain constant, or approximately so. These through I were used to estimate the applicable periods of complete data for each seismic region. Three alternative methods were used to establish the list of earthquakes.

### 3.2.2 Attenuation

The seismicity model discussed above expresses the probability distribution of events at the epicentre. However, the effect of such an earthquake rapidly diminishes with distance. This phenomenon is represented by an attenuation model. Various expressions have been suggested to represent the attenuation of earthquake waves due to the distance between the epicentre and the site (Howell, B.F. (Jr.) and Schultz, T.R., 1975). Isoseismal maps can be used to derive a suitable expression for Southern Africa. Typically, the intensity at a site (I) is expressed as a function of the intensity at the epicentre, the epicentral distance (R) and the focal depth (h).

### 3.2.3 Engineering manifestations of earthquakes

In the design of a structure, it is necessary to predict its response by using engineering input parameters, such as the peak ground acceleration, or the response spectrum for the design earthquake. MMI values cannot be used for this purpose.
No strong motion records are available of any significant natural earthquakes in Southern Africa. Functionals expressing the peak acceleration, response and Fourier amplitude spectra as functions of the site intensity have been proposed, and are based on a large number of world-wide earthquakes (Anderson and Trifunac, 1979; Cornell, Banon and Shakal, 1975; Trifunac and Brady, 1975). These correlations represent the relationship between two site parameters (e.g. MMI and peak acceleration), and are not significantly influenced by the geological characteristics of the region. This data can therefore be transferred from one seismic area to the next, and can be used to develop seismic input parameters for sites in Southern Africa.

3.2.4 **Final model**

The above expressions and functionals were obtained from observed data, and inherently exhibit a certain degree of scatter. Therefore, they need to be treated as probability distributions. Using this data, it is possible to derive a probabilistic model of the response at a given site by considering the seismicity of all seismic sources in the vicinity, by attenuating the effect to the site, by converting the MMI value to the response variable of interest, and then by integrating these functions for all seismic sources to obtain, for example, the response spectrum values at a range of frequencies. The response spectra obtained from these models can easily be used to generate the design time histories by using other methods for generating artificial earthquakes that are compatible with the design response spectra (Gasparini and Vanmarcke, 1976).

It is beyond the scope of this paper to further discuss the details, but the methods are more fully explained in the work of Cornell (1968), and Anderson and Trifunac. Models for the seismicity and attenuating effects have been developed for the Southern African region, and are discussed in the following sections.

3.3 **Seismic Design Principles**

It was pointed out above that the dynamic interaction between the structure and the supporting soil needs to be taken into account. A complex model is being developed for this purpose: in this particular site, it can be expected that the dynamic interaction between the horizontally layered sand and the structure could be quite substantial. Care will be taken to ensure that a resonant situation is not created. At other sites, special care will be needed to prevent such interaction. Where possible, a more rigid site should be selected, as that would obviate the use of special soil improvement techniques (e.g. piling, large foundation mats, etc).

Should the site characteristics require it, it may be necessary adapt the structural layout in one of the following ways:

- modify the structural layout to change its dynamic behaviour
- consider alternative support positions for equipment (which should at all costs not be done)
- use more flexible support elements

This may require some additional attention when designing the plant for a subsequent project.
3.4 **Design Philosophy**

The general philosophy being followed in this project is to provide a design that would withstand a certain level of seismic excitation for at least 0.5g: the current design level is 0.3g, but it is anticipated that the target will be achieved without serious design repercussions. This will allow the design to be used on a wide range of sites throughout the world, without having to be requalified.

3.5 **Seismic Analyses**

A dynamic analysis model of the system and the structure will be compiled, which will represent the dynamic properties of the various components. However, in order to optimise the structural layout, and to provide meaningful input to the designers of the process equipment, a phased approach is being followed in modelling the systems. In the development, four levels of models are will be developed. These are the following:

- 2 Planning models (100 - 200 elements), one consisting of individual models for the building and process equipment, and one consisting of a combined model for both systems
- Design model (500 - 3000 elements)
- Licensing model (3000 - 10 000 elements)

The different types of analyses to be performed are outlined below.

3.5.1 **Response Spectrum Analysis**

A decoupled 3-D dynamic analysis of the primary loop will be performed. In this analysis, a floor response spectrum will be generated for the operating level of the concrete structure using the dynamic properties of the concrete structure. In this decoupled analysis of the concrete structure, the primary loop will be modelled as lumped masses to reflect the interaction effect between the primary loop and the internal concrete structure.

In the second analysis, the complete piping system, and the concrete structure will be considered. The primary loop will be once again connected to the internal structure as discussed above. The basemat will be represented by a six degree of freedom model which will allow complete freedom to rotate and displace, but which assumed that the basemat itself will be rigid, thereby representing the soil-structure interaction.

A computer program (SSICAL) has been developed in-house for the purpose of calculating the dynamic soil-structure interaction. It is based on the Substructure Theorem, and encompasses a model synthesis in the frequency domain. This technique recognises the fact that the natural frequencies and model shapes of a structure with a fixed base are easily obtainable, while the soil is characterised by frequency-dependent stiffness functions.

An equivalent (frequency dependent) dynamic stiffness matrix can be compiled which represents the dynamic properties of the structures and the soil. For this, it is necessary to
calculate the mode shapes of the structure on fixed base (i.e., ignoring all soil-structure interaction). The study will consist of the following steps:

- develop models for the structures, and calculate the modes and frequencies on a rigid base;
- generate the time histories, and calculate the Fourier transfers of each;
- calculate the dynamic stiffness of the combined model, and then calculate the response at each frequency;
- calculate the inverse Fourier transfers for each record to obtain time histories for the displacement and rotation of the base; and
- evaluate the response of the structures and pipes, using the time histories and prescribed displacements.

3.5.2 Combined Model

Since the concrete structure supports the primary loop, and as the primary loop will be quite heavy compared with the internal concrete structure itself, the primary loop model will be incorporated in the internal concrete structure model to form a combined model so that the interaction of these two substructures could be accounted for.

The coupling of the primary loop and the concrete structure will be achieved by means of sub-structuring and the use of generalised constraints equations for constraining the supports of the primary loop to their respective support locations in the internal structure. In this analysis, the primary loop will be considered as the higher level substructure and the internal concrete structure as the lower. The support locations were selected nodes in the internal structure, and were constrained to the six degrees-of-freedom of the beam element modelled in the centre of the structure. Since the structure will be supported on a rigid base, no interaction could occur between the internal and containment structures. The latter structures were therefore excluded from this analysis.

3.5.3 Licensing Model

This model will consist of a very detailed set of components in which the different key elements will be assessed. Detailed stress calculation will be performed, as will the accelerations be calculated for sensitive equipment.

4. Summary

This paper briefly reviews the scope of work being undertaken to address the seismic analysis and structural design of the proposed new facility. It is pointed out that methods are available for compiling seismic histories for the facility, even in the absence of comprehensive seismic histories.

The importance of the seismic and structural inputs have been highlighted, and the importance is stressed regarding the role of the structure in providing appropriate support, stiffness and protection to the equipment. It is clear that these issues will be of significant importance during the licensing applications, and appropriate attention needs to be given to the matters.