SEISMIC DESIGN OF INDUSTRIAL STRUCTURES IN CHILE

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SYNOPSIS

Seismic design practice for industrial structures, as developed in Chile since 1945, is described in this paper. A summary of research, specifications and design methods for the most common structures found in industrial projects is presented. The problems of project coordination between foreign and local engineers for adequate seismic analysis is analyzed. Consideration is also given to indirect and shutdown losses after a major earthquake, that are often far more important than direct structural losses.

Chile, located in the Circumpacific Belt in the S.W. part of South America, is one of the most active seismic areas of the world. The country built the bulk of its heavy industry since 1945. During the intervening period, it has suffered six major earthquakes of Richter magnitude 7.5 or more.

Because the seismic behaviour of structures designed by the methods described has been successful, and because the literature on the subject of earthquake design in industry is rare, it is hoped that the Chilean experience may be of interest to practicing structural engineers responsible for the design of industrial installations in seismic areas.

RESUME

Le Chili se trouve dans une partie du globe particulièrement susceptible à des grands tremblements de terre. On présente un état des connaissances sur les méthodes de conception, les recherches effectuées, et les normes existantes qui touchent les structures industrielles de ce pays. Des problèmes de coopération avec des ingénieurs d'autres pays ainsi que des pertes de temps occasionnés par les séismes sont élaborés. Vu l'excellent rendement de ces structures, on peut prendre avantage de cette expérience.

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SUMMARY

1. INTRODUCTION

Chile is generally regarded as having one of the highest seismic activities in the world. According to Lamnitz (1), in the country's history since 1535, there is evidence of more than 15000 events (1 every 10 days), 30 of them major earthquakes of Richter magnitude 7.5 or higher. The historical frequency of destructive earthquakes is, therefore, of 1 every 14.5 years, but this figure is probably low because in the last century, with more reliable information, a frequency of 1 every 6.9 years has been recorded.

The high seismicity is explained by the geophysical configuration of the area. As shown in Figure 1, the country, with a length of 4200 km and an average width of 240 km, is located in the southern tip of the Circumpacific Belt and has two parallel mountain chains in its length, the Andes and the Coastal Ranges, with differences in elevation in Central Chile, between Mount Aconcagua (7021 m) and the Pacific Ocean (-5000 m) of 12000 m in 240 km. This steep slope is characteristic of the seismic zone of Chile that extends over 2/3 of its length, north of the 42nd parallel. The so-called Chilean Rise, a probable transformed fault is the result of a process of buckling and underthrust of the continental border because there is evidence that the South American Continent is drifting westward against the oceanic crust while the Pacific basin is simultaneously spreading against the Chilean coast at an estimated rate of 5 to 6 cm per year (1).

Chilean earthquakes are due to large scale crustal movements. Epicentres are normally located offshore, 40 to 150 km from the coast, with depths of focus in the order of 50 km. Because of the epicentral distance and deep focus, destructive earthquakes have a high Richter magnitude, 7.5 or over according to Lomnitz. Up to now, attempts of seismic zoning have proven impractical and it seems that, north of the 42nd parallel, the whole country should be considered as one single high-intensity area. Zones of lower intensity are found, at any latitude, in the highlands of the Andes (except for pockets of recent sediment in mountain, lake and valley) as well as in the southern plains around the Strait of Magellan.

The shift from an agricultural to an industrial economy took place in Chile at the end of World War II when the country started the construction of its heavy industry. In the ensuing decades, Iron, Steel, Oil, Pulp, Paper, Cement, Sugar, Hydroelectrical and Petrochemical industries were built and Copper Mining was expanded several fold. Most of these industries are located in the high intensity zone, in the valleys north of parallel 42. Throughout these years seismic design methods were developed and tested in the periodical earthquakes. The industrial installations, thus built, have resisted successfully six major events, of magnitude between 7.5 and 8.5, among them the May 21 and 22 (1960) series of earthquakes that, according to the opinion given by Housner in 1963 rank with the very greatest in seismic history and are more than the equivalent of accumulated destructive earthquakes in California in the sixty previous years (2).

Chilean seismic design history as is often the case in our profession, lies in the offices of many private and governmental organizations. This paper is an effort to synthesize the main criteria of the accumulated experience, as seen by the writer, who has participated in the seismic design of industrial structures in his country for more than 30 years. It is written by a practising structural engineer, and, within the limitations of representing a personal point of view, it is hoped that it may be of use to other practising engineers engaged in the design of industrial structures (Note 1).

Note 1. A companion paper was presented by the writer to the 2nd Chilean Conference on Earthquake Engineering in 1977. This paper is based on that paper but incorporates valuable suggestions received from other engineers as well as changes that have taken place since.

2. PROJECT COORDINATION

Large industrial projects in Chile are normally done by engineering groups in the developed countries of the northern hemisphere in cooperation with local engineers. The relationship between the foreign and the local teams may assume a variety of forms, the most common being joint ventures, subcontracts or independent work for the same customer. As a rule, the foreign engineering group is responsible for basic engineering and the Chilean team for civil and structural design.

Under these conditions, adequate project coordination, from the standpoint of seismic design, has an importance that is equal to, if not greater than, the technical matters involved. In the author's opinion, far more failures, delays and loss of time and good will can be traced to inadequate coordination than to faulty engineering.

The matter is aggravated because very often the Chilean customer and the foreign consultant do not clearly understand the importance of earthquake design. Problems are more common when the foreign firm is located in non-seismic areas as well as in the case of special structures in which it is difficult to separate the process from the structural design. Amazingly enough, distance and language have not proven to be a problem.

Adequate coordination has been achieved in many projects done by local engineers and foreign firms with experience in the country. Procedures may vary but are generally based on the following methodology:

- A special Seismic Design specification for the project should be available from the beginning. If the customer does not have one, insist on it or prepare one.

- The specification should make a clear distinction between normal structures, that can be designed by conventional methods and special structures that require a different treatment. The latter should be identified and listed in the specification.

- In special structures the following minimum requirements are recommended: an experienced earthquake engineer responsible to the customer must participate in the phases of structural planning and concept development; designs done by the static method should be checked by dynamic analysis; and finally, all drawings, computation sheets and computer programs and print-outs must have the customer's approval.

- In the case of large pieces of equipment designed by the manufacturers, incorporate the seismic design specifications in the invitation to bid. Since manufacturers often underestimate the effect of earthquake design in their proposals, it is recommended to request a unit price for variations in structural weight and, for budgetary purposes, to assume between 10% and 20% excess weight over the quoted figures.

3. DESIGN BASIS

3.1 Design Methods

National and City Building Codes have been developed for various dwellings and tall buildings which contain some of the following common properties: damping coefficients from 5 to 8%, fairly uniform distribution of masses along the height, and rigid diaphragms at floor levels.

Industrial structures rarely meet the above requirements: damping varies from 1 to 3%, mass distribution is erratic with large concentrations at any elevation and there are few rigid floor diaphragms. Furthermore, they have other features seldom found in conventional buildings such as large eccentricities, friction type connections (e.g. wheel to rail) and structural elements that work at very high temperatures, such as in refractory masonry and fired pressure vessels.

For these reasons, the non discriminatory use of Building Codes in industrial structures is not only inadequate but very often dangerous; thereby the need of special methods for earthquake engineering.

In Chile the Static and Dynamic methods of analysis and design are normally specified.

The static method is applied to conventional structures, with relatively simple distribution of masses and small eccentricities, such as Mill Buildings, Platforms, Conveyor Galleries and the like.

Dynamic analysis is required for very important, as well as, special structures such as Blast Furnaces, Tall Vessels, Stacks, Heavy Bins, Elevated Tanks, field-erected Boilers and Large Mobile Equipment (Unloading Towers, Cantilever Cranes, Stackers, etc.).

When dynamic analysis is required, preliminary sizing is made by the static method. It is usually specified, as an added precaution, that if dynamic effect is less than 80% of the static, the latter governs. This requirement is a recognition of the design practices successfully used before the advent of dynamic analysis in the sixties.

3.2 Static Method

Seismic coefficients for base shear of main structures varies from 0.15g to 0.30g as shown in Table 1. It is noted that two seismic zones are recognized:

- Normal seismicity area; and

- Low seismicity areas, south of the 47th parallel as well as the Andes highlands. The latter should be proved in each case by a risk analysis.

Vertical seismic accelerations are also specified for special structures such as large mobile equipment, suspended boilers and tall vessels.

Vertical distribution of seismic forces is done in accordance with either the Chilean Code NCh 433 (3) or the Uniform Building Code. For seismic eccentricity when floor diaphragms are present NCh 433 is used.

Applicable Chilean Code formulas are the following:

$$Fx = V \frac{Px\ Ax}{\Sigma Px\ Ax}$$

$$Ax = 1- \frac{hx-1}{H} - \frac{1-hx}{H}$$

$$e = 1.5e_o \pm 0.05\ a$$

Where

Fx is the seismic force at elevation "x"
Px is the weight at elevation "x"
V is the base shear
hx is the height of mass at level "x"
H is the height of the tallest mass
e is the design eccentricity
e_o is the theoretical eccontricity
a is the largest plan dimension normal to the earthquake

Design stress levels are as specified in AISC, ACI or the equivalent Chilean Codes.

3.3 Dynamic Method

Dynamic methods were first proposed after the May 21, 1960 earthquakes by J.A. Blume (4) who analyzed their effects on the Huachipato Steel Plant, in the bay of San Vicente, near Concepcion, Figure 1. In his opinion, Huachipato was probably exposed to the most severe seismic exposure to date of any major industrial installation in the world. The plant resisted the earthquake remarkably well, structural damages were less than 0.5% of total investment and operation partially started after 3 days and became normal 6 days after the shock (5).

Blume made a comprehensive analysis of 16 of the plant structures with periods ranging from 0.44 to 2.45 seconds, 9 that were undamaged and 7 that experienced minor failures such as shell buckling of stacks and anchor bolt stretch. Based on these studies Blume determined the Huachipato Acceleration Spectrum shown in Figure 2. For references the NS-1940 El Centro smoothed spectrum is shown in the same graph. In Blume's opinion the spectrum is reliable between 0.6 and 1.2 seconds and too low for high periods (4). Based on Blume's pioneer paper, Professor Rodrigo Flores developed the design spectrum also shown in Figure 2. The Flores Spectrum has been used in practically all the important industrial projects done in Chile in the last 15 years.

Professor P. Ruiz (6, 7) later proposed spectra for low seismicity areas and for vertical accelerations, the ordinates of which are approximately equal to 50% of the normal Flores spectrum.

Modal superposition is done in accordance with NCh 433, using the average between the arithmetic and the quadratic sum of the modes.

$$S = \frac{1}{2} \left[\Sigma S_k + \Sigma S^2{}_k \right]$$

Sufficient modes to account for at least 95% of the total mass, but not less than 5, are incorporated in the analysis.

Because of the complexity of industrial structures, effects such as axial load deformations, horizontal displacements due to rocking motion and horizontal torsion must be analyzed by means of space programs such as STRUDL II (8) or others developed in Chile (9).

3.4 Live Load Reduction and Load Combinations

In conventional buildings live loads are not considered (UBC) or are reduced to 25% of normal values (NCh 433) for seismic design. In industrial structures, the matter must be carefully analyzed with the operators to judge the probability of concurrency of the specified live load with a major earthquake. For example, in the charging floor of a BOF Steel Shop a normal live load of 2.5 MT/sq.m. was specified, but after discussions with the operators, it was found that it would happen occasionally, during relinings, and that in no case would it cover more than 10% of the total area. Consequently, seismic design was made with no live load. Table 2 can be used as a guideline for live load reduction, but in no case should it replace an analysis done together with the operators.

Other operating loads that must be considered for seismic design are also a matter of judgement and analysis with the plant engineers. The writer has not found any literature on the subject with the exception of the Association of Iron and Steel Engineers Standard N° 13 (10) that specifies the following loads to be used in combination with earthquake effects in Steel Plants:

- Dead loads plus reduced live loads plus equipment weight plus full silos and bins.

- Above loads plus the weight of one or more unloaded overhead cranes placed in the most unfavorable position.

While the recommendations seem to be sound for Steel Plants, there seems to be no doubt that the subject requires further analysis in each industrial application.

4. MILL BUILDINGS

4.1 Earthquake Performance

Mill buildings in Chile are designed in accordance with the local steel code that is patterned after AISC, the main differences being that the Chilean Code allows larger slenderness ratios, 250 in compression and 350 in tension, and discourages the use of diagonal bracing capable of working in tension only. In design practice, columns are usually built-in, crane girders simply supported, and roof bracing is generous.

The seismic behavior of mill buildings thus designed has been excellent; no case of major failure is known and observed damages have been limited to the problems of detail examined below.

4.2 Overhead Cranes

In the great earthquakes of May 1960, several overhead cranes bent their rails, left the tracks and came to rest with wheels dangerously close to the girder edges. Other widely observed damage was the cracking of plate diaphragms at the crane girder supports.

None of the above can be rationally explained by conventional analysis, specially if it is considered that seismic forces are usually smaller than lateral crane thrusts or wind loads.

The earthquake response of a crane with a suspended swinging load is a complex problem that requires dynamic analysis. L. Loyer, at the Catholic University of Chile, investigated the dynamic response of 4 mill buildings, of the type illustrated in figure 3a, with crane capacities ranging from 10 MT to 160 MT, spans from 12 to 33.5 m and rail height from 7.3 to 20 m (11). The structural model is shown in figure 3b, while the masses "m" and rigidities "k" are shown in 3a. J_1 and J_2 are friction type joints between the crane and trolley wheels and the rails, and Coulomb type stress-strain properties as shown in Figure 3c.

Modal analysis using the Flores spectrum was made for more than 600 cases with variable loads and cable lengths. It was initially assumed that the system remained elastic, with no sliding at J_1 and J_2. The results are summarized in the design spectrum of Figure 3d. The spectrum is based on a "pseudo period" that can be easily computed assuming that the hanging load is rigidly attached to the bridge. It can be noted that for periods larger than 1 second, the most common in mill buildings, the fact that the load is suspended increases the base shear.

If wheel sliding takes place, seismic forces can be expected to decrease because of the energy absorbed by friction. Because the dynamic study of the sliding model of Figures 2b and 2c proved to be too involved, the problem was analyzed by approximated methods based on the theories developed by Newmark for seismic systems with friction joints (12). It was found that the trolley slides in practically all cases and the bridge in most cases. Movements of the trolley have no practical consequences, but sliding of the bridge truck wheels can explain the impact damages observed in 1960.

Even though the investigation is not conclusive, it seems that damages can be avoided if wheels and rails are designed to minimize the effects of lateral impacts. Figure 4a shows a suggested detail, with self centering wheels and rounded-head rails on elastic supports that has been used with good results in several projects after 1960.

Figure 4a also shows two additional details that are standard practice in Chile, the uplift clamp and the horizontal draphragm. The uplift clamp is a device to prevent the bridge from jumping off the rails, an accident difficult to explain but which has been observed. The horizontal diaphragm has been used to avoid the extensive cracking observed in 1960 in the conventional vertical diaphragms shown with dotted lines. Cracking is probably due to a combination of fatigue and seismic impacts.

4.3 Drift

Horizontal seismic deformation or drift is seldom a design condition in mill buildings that have few nonstructural elements subject to deformation damages. Drift was investigated by Loyer (11) who found unusually large lateral deflection at crane rail elevations, from 1/50 to 1/185 of the height. These high drift figures were confirmed by scratches left by broken diagonals in one of the buildings analyzed that resisted successfully the 1960 earthquake. The conclusion seems to be that the normal practice of not limiting drift in mill buildings is justified, but that the $P-\Delta$ effect should always be a design factor.

Minor damages of adjacent building structures knocking each other, mainly at expansion joints, are common and can be explained by the high drift values. It is recommended to provide a structural separation at least equal to twice the sum of the maximum horizontal deformation of both structures.

Foundation uplift up to 1/3 of the contact area is allowed in ordinary buildings. In important structures, full contact is always required.

4.4 Details

The most common damages observed in mill buildings were cracks in masonry walls, stretched anchor bolts, and broken bracing in front walls.

Masonry cracks are due to the inability of brick or concrete blocks to follow the deformation of steel structures. The Connection detail shown in Figure 4b, that allows for independent movement and provides lateral support has been successful in preventing cracks.

It has been found that most anchor bolts, which apparently act as the safety fuse of a structure, stretch during important earthquakes. Inspection, tightening and repairing of anchor bolts is therefore one of the first and most important tasks after the event. The base detail shown in figure 4c, that has ample thread for retightening and a stem accessible for inspection and repairs is commonly used in Chile. Except for minor columns, shear keys should always be provided because bond, friction and bolts have proven to be very unreliable in resisting lateral forces.

Figure 4d shows a front wall. If full bracing is placed as indicated by dotted lines, the wall is far more rigid than the neighboring frames and diagonal failure by buckling is almost certain. Inasmuch as the only purpose of front wall bracing is to furnish lateral support of the wind columns, it should be flexible and not carried to the ground, as indicated with solid lines in Figure 4d.

5. LARGE MOBILE EQUIPMENT

5.1 Earthquake Performance

Most heavy industries have large size mobile equipment, usually track mounted, such as unloading towers, stackers, cantilever cranes and the like, some of which are shown in Figure 5. These pieces of equipment are generally important, expensive and critical structures that, in case of a major failure, may cause prolonged shutdown of the industry.

The main seismic risks are the following:

- Overturning, due to a combination of eccentric weights and lateral forces. Anemometer-actuated rail clamps, provided to prevent overturning by wind, are obviously not effective in earthquakes.

- Rocking, a phenomenon in which the wheels on both tracks alternatively lift and descend, knocking the rails.

- Sliding impact of wheel rims on rail heads and

- Horizontal seismic torsion of the long booms.

5.2 Overturning

It is generally accepted that due to the alternating nature of seismic forces overturning is not an earthquake danger even for slender structures (13, 14). The application of this criterion to tall cranes and towers with very eccentric vertical loads is not so clear and may even be dangerous. Several port cranes overturned during the May 22, 1960 earthquake in Puerto Montt, Chile and the February 29, 1960, El Agadir earthquake (15), but apparently in both cases the collapses were due to a combination of seismic forces with soil settlement.

5.3 Rocking and Sliding

The mechanics of rocking were studied by Houssner (13) for solid blocks as shown in Figure 6a. The horizontal force "H" induces a rotation around point "O", but if reversal of H takes place before stability is lost, rocking but not overturning takes place.

Two "pseudo static" factors-of-safety can be established:

$s_1 = Pa/Hh$ for overturning
$s_2 = mP/H$ for sliding

where P is the weight, H the lateral force, a and h dimensions shown in Figure 6 and "m", the wheel to rail coefficient of friction.

If the "pseudo static" factors are less than unity, rocking and sliding take place.

Truck, wheel and rail damages due to rocking and sliding were common during the 1960 earthquakes in Chile. Apparently, if the "pseudo static" coefficients are over 0.9, damages are minor: if they are around 0.8 they may be serious and, if below 0.6, overturning may be a danger.

In Chilean practice, overturning and sliding are prevented by adding sufficient counterweights, placed as low as possible, to have a minimum "pseudo static" factor of safety of 1.2. It should be warned, nevertheless, that in cases of standard equipment in which the earthquake condition is not considered when establishing the structural concept, counterweights may be as much as 30% of the equipment weight, originating structural problems and affecting the efficiency of operation.

The use of sliding clamps to limit rocking and sliding, as shown in Figure 6b has been suggested but, to the writer's knowledge, not used. Apparently, they originate operation and maintenance problems that are not easily solved.

5.4 Horizontal seismic torsion

Horizontal seismic torsion due to earthquake forces normal to the boom, see Figure 5c, is very often critical and almost always ignored in the manufacturer's design. Weak elements are usually the boom-connecting pins, the counterweight links, and the turntable gears (Figures 5c and 6d).

5.5 Design recommendations

Preliminary design, stability analysis, and sizing of counterweights is normally done by the static method, with both horizontal and vertical accelerations and pseudo-static safety factors of 1.2.

A modal dynamic analysis should always follow, with the horizontal and vertical spectra acting simultaneously. It is recommended to place the load in the most critical position for overturning or torsion and to assume that it is rigidly attached to the boom; this assumption is justified by investigations (11) as well as because the load is usually small when compared to other weights.

Dynamic analysis is made of the counterweights to prevent rocking in place and the recommended minimum safety factors for sliding and overturning are also 1.2.

In actual practice, stability conditions are seldom met by equipment of standard non-earthquake design.

6. BOILERS AND HEAVY HANGING EQUIPMENT

6.1 Earthquake performance

Heavy hanging equipment, such as field-erected boilers, are common in large industrial installations. In non-seismic areas, boilers are freely suspended in order to permit vertical (expansion) and horizontal (breathing) temperature movements.

More than 20 top suspended boilers have been built in Chile in the last 20 years, in the power, steel, pulp, paper and copper industries, with heights ranging from 25 m to 65 m and weights from 1500 MT to 4000 MT. The largest-known boiler is probably the TVA 1200 MW units, at the Paradise Plant in Kentucky, that weighs 11000 MT and has a height of 170 m (16). A boiler failure not only involves substantial direct and shutdown losses, but also high fire and explosion risks. Because of these reasons, boilers are now classified as "lifeline structures" and seismic design must be specially careful.

Only one case of collapse is known in Chile, of a non-earthquake designed medium-sized European boiler. Many free-swinging boilers, built before 1960, have hit the surrounding structures causing extensive damages to columns, beams and bracing as well as rupture of pipes (17). Extensive repair and reinforcing have been required but the main losses were due to the prolonged shutdowns. The earthquake record of properly designed boilers is good.

6.2 Structural concept

Figure 7a shows a typical boiler suspended at the top from a six-column surrounding structure.

Earthquake ties between the boiler and the frame, capable of resisting lateral forces without interfering with expansion should be provided at different heights, preferably on all floors. Figure 8a shows a set of tie bars, the most commonly used solution. Earthquake guides located at the temperature neutral axis as illustrated in Figure 8b have been applied in larger size units. In one case, of a very heavy BOF hood that, because of its rigidity created structural problems, elastomeric dampers of the type shown in Figure 8c were specified.

Free-swinging boiler installations are possible if sufficient separation to avoid knocking is provided. In Chile they have not been used, perhaps because it is felt that methods of analysis are not sufficiently reliable for the risk involved, as well as because of the complications of connections to piping and surrounding structures.

Anchor bolts are normally of substantial size and difficult to repair if failure takes place in the embedded stem. The "hammerhead" bolts shown in Figure 8d are recommended; in addition to their good energy absorption capacity, they can be easily removed for inspection, replacement or repair.

Connection to neighboring structures or pieces of equipment, such as uptakes, large piping or preheaters should have ample flexibility to accomodate diferential movements; stainless steel and asbestos expansions joints, designed for twice the calculated sum of seismic movements, of the type illustrated in Figure 7a are recommended.

Rigid-frame construction is preferred to diagonal bracing for the main structure, to take advantage of its energy-reserve capacity and inherently higher safety factors in elements as critical as large boilers.

6.3 Design recommendations

In large field erected boilers, more than in other structures, coordination between seismic and process design, commented upon in section 2, is necessary.

The basic structural concept, column locations, selection of floor levels and layout of earthquake ties should be jointly done by boiler and seismic engineers.

Once a satisfactory structure is established, a static analysis, preferably by computation, should be done to size all members and to figure out deformations. The resulting forces and deflections at the connection points must be used to check boiler elements such as buckstays, shells, inside piping, etc. Both horizontal and vertical accelerations have to be considered, when the boiler is suspended by hangers with springs.

Finally the design should be checked by a modal analysis, using a horizontal and a vertical spectrum. The structural model is shown in Figure 7b, in which "k" and "m" are the frame, and "K" and "M" the boiler rigidities. Experience shows that changes due to the dynamic analysis are usually small and easily made during fabrication or erection.

7. PIPING

Figure 9 shows a pipeline that runs from a boiler drum to a yard at a lower level, passing through a building. The most important feature of seismic design is the layout of supports, as shown in the figure, that furnish lateral stability for each section without restricting temperature movements. Usually, simple measures such as the replacement of conventional hangers by V-type hangers (supports 3B, 2B and 2C) or the addition of slotted holes (supports 2A and 1A) are sufficient.

Seismic analysis should be made of critical piping containing explosive, inflammable, toxic or valuable liquids or gases, in high pressure networks, and in essential services such as fire-fighting systems.

Generally seismic deformations at support points, in the x, y and z directions, are independent of the piping system and are imposed by structures such as the boiler, the building and the towers in Figure 9. If such is the case, the deformations, as obtained from the structural analysis, can be used as input to any conventional piping program. Seismic dynamic analysis programs have been developed for piping systems (18) in which the supports are replaced by equivalent springs and masses. The use of these programs is justified only in very critical cases.

8. TALL AND SLENDER STRUCTURES

8.1 Earthquake performance

Figure 10 shows a number of typical tall and slender structures usually found in industry. The seismic behaviour of these structures during Chilean earthquakes has been good; no cases of collapse are known and damages can be classified as minor.

Figure 10a is a sketch of the Huachipato blast furnaces, that have resisted all earthquakes with no damages whatsoever. The key feature is the lower support, in which the mantle, columns and bottom rings are welded box-sections with good bending and torsional resistance in all directions.

Figures 10b and 10c are tall process vessels and stacks. Damages have been confined to shell buckling, column to shell connections, and anchor bolt stretching.

Figure 10d shows an inverted-pendulum and a conventional tower-supported water tanks. No damages have been detected in the first type. In the tower-type tanks, failure of round bar diagonals is common but, somehow, the tanks have not collapsed.

8.2 Design recommendations

Preliminary sizing is based on the static method, using the horizontal and vertical seismic coefficients of table 1 and vertical distribution in accordance with UBC or NCh 433.

Stacks and tall vessels designed, with the Huachipato bending moment distribution shown in Figure 10e, were undamaged in the 1960 earthquakes. After his field studies and theoretical analysis, Blume (4) recommended the reduced diagram indicated by dotted lines in the same Figure.

For period calculation, the effect of lining should be included but shear deformation and soil rotations may be neglected. These conclusions, valid for medium or hard soils, were reached by Blume in his Huachipato studies and confirmed by site measurements made by Cloud (19) after the 1960 earthquakes. From his analysis of observed failures, Blume proposed a shell buckling formula that is slightly more conservative than Timoshenko's theorical one. Applying, for the seismic condition, factors of safety of 1.25 against yield and 2.0 for stability, the following design formula is obtained:

$$F = 365 \frac{e}{d} \leqslant 0.8 F_f$$

where "F" and "F_f" are the allowable unit and yield stresses in MT per sq.cm., "e" is the shell thickness and "d" the cylinder diameter.

In column-supported vessels, of the type shown in Figure 10b, damages are usually located in the column to shell connection. Design based on a dynamic analysis and on Brownell and Young formulas (22) has been found to be adequate.

Tension diagonals of the tower-type tank shown in Figure 10d, should be prestressed to approximately 10% of yield to avoid the impact effect caused by the seismic shock when they are loose. Initial tension can be controlled by giving to sag the following value:

$$d = 3.6 \left(\frac{2.7}{F_1}\right) \left(\frac{L}{10}\right)^2$$

where "d" is the sag in cm, "L" the span in meters and "F_f" the yield point in MT per sq.cm. It is better yet to design with compression bracing.

The dynamic behaviour of liquid inside the tank has been studied by many investigators (20, 21). Nevertheless, for the size of tanks commonly found in industry, it is sufficiently accurate in lateral forces analysis to replace the liquid by a solid mass of 80% of its weight.

Foundations for structures of this type should always be designed with full contact area, allowing no uplift.

9. FIELD STORAGE TANKS

Movement of liquid inside oil or similar field storage tanks, as shown in Figure 11, is very complex and causes large deformations of the roof, shell and bottom plates. In actual practice it is not possible to control the deformations and it is best to allow them to happen, designing suitable details to avoid local damages.

J.E. Rinne (23) made an excellent report on damages to oil tanks during the Alaska 1964 earthquake. His design recommendations, summarized below, have been confirmed in Chilean practice:

- liquid movement induces over and under pressures that may cause failure of roof beams and plates, general buckling of the upper shell ring, local buckling at the lower shell plates and tearing of column bases. Damages can be avoided with flexible details such as shown in Figures 11b and c;

- lateral forces induce uplift of the bottom, see Figure 11a, and sometimes cause the tank to move away from the foundations. Anchor bolts are not capable of controlling these effects and normally fail. It is more practical to allow the uplift to happen and to build the bottom as a cone with 1% slope.

- floating roof tank seals, illustrated in Figure 11d commonly become stuck. It is easier to repair them than to prevent this minor damage; and

- to prevent shell buckling Rinne recommends the following minimum thickness for the bottom ring:

$$e \geqslant \frac{H}{27}\sqrt{CD_p}$$

where "e" is the thickness in cm., "H" and "D" the tank height and diameter in m, "C" the seismic coefficient and "p" the liquid unit weight in MT per cubic meter.

10. INDUSTRIAL MASONRY

Refractory brick masonry, operating at high temperature, are common in industry. Theoretical analysis is difficult, because rigidity and strength of brick at high temperature is seldom known, and, very often, structural resistance depends on the pressure between units caused by heat expansion.

In spite of the above, the seismic record of Blast Furnaces, Coke Ovens, Open Hearths, Reverberating Furnaces and similar masonry structures in Chile has been remarkably good. The following design practice is followed:

- in very large ovens, such as the Huachipato Coke Battery shown in Figure 12a, provide intermediate and end reinforced-concrete pinion walls.

- in Open Hearth, Reverberatory and similar furnaces, the outside steel work should have ample lateral and longitudinal seismic strength. Allowance for initial heating expansion should be made and suspended roofs are preferably to arc roofs, see Figures 12b and 12c.

- in the pattern of the brickwork itself try, whenever possible, to provide for some lateral strength. Sometimes, simple structural calculations of the brickwork can be made. If seismic stresses are less than 33% to 50% of the stresses due to operation such as weight, temperature and pressure, earthquake damage will probably be avoided.

11. SECONDARY STRUCTURES

Every industry has a certain amount of equipment and other secondary structures that routinely, are not submitted to structural analysis. Typical of the type are the pressure filter, the transformer and the package boiler shown in Figure 13a, b and c. Many of these structures have little or no lateral strength and may fail, causing important shutdown or secondary losses. Seismic reinforcement is usually very simple, such as the bracing of the filter legs of Figure 12a, the wheel stops of the transformer of Figure 12b and the anchor bolts of the boiler of Figure 12c.

It is a good practice to submit all equipment drawings to the seismic engineer for review, no matter how unimportant or unrelated to seismic effects they may seem.

12. INDIRECT LOSSES

Structural damages in a well designed industry can be reduced to a very low value, of a fraction of 1% of total investment. Far more important, usually, are the indirect losses due to explosion, fires, loss of production and idle investment during the prolonged shutdowns required for inspection and repairs of a large number of small failures.

Unfortunately, this important fact is generally ignored by earthquake engineers who should, in addition to the design of main structure, give careful attention to the following:

- maintenance of vital services that must be operative after the earthquake to avoid fires, explosions or irreparable damage to important operating units:

- seismic check and overdesign of minor equipment that, in case of failure, may cause long shutdown; and

- details designed for easy inspection and repair.

To illustrate the point two actual cases will be quoted.

In the 1964 La Ligua earthquake in Chile, several tanks of the water-treatment plant of an important power plant, of the type shown in Figure 13a, collapsed. Structural losses were very small and out of proportion when compared to the 3 days power shutdown that was the result.

The Huachipato Steel Plant had, in 1960, what was believed to be a well-conceived system of services with emergency units that included a 30000 cu.m. water reservoir built on top of a nearby hill, a 2500 KVA steam-driven stand-by generator, an emergency steam-driven blast-furnace blower and two multifueled boilers.

In the May 21, 1960 earthquake, when public power failed, water from the reservoir could have kept the blast-furnace cooling system in operation. Unfortunately, however, a 36" underground main broke and drained the reservoir in 35 minutes. No recirculation to save water at the blast furnace was possible since power was not available. Power could not be produced in the emergency generators because steam was not available, first due to broken pipes, and, secondly, to earthquake damages to the coke-breeze aprons. Broken gas mains could not be steam purged and the danger of explosion was ever present. When public power was restored, only 1.5 hours after the shock, it was found that the electrical lines to the river pump-station were grounded due to the failure of several pin-type insulators and no water could be pumped.

Eventually water was pumped, steam became available to purge the gas mains and gas could be produced to keep the coke ovens hot. Nevertheless a delay of as little as half an hour could have caused a major disaster such as gas main explosions, coke-oven collapses or overheating of the blast furnace. The vulnerability of the plant was dramatically illustrated and has been corrected since.

Exposed-stem anchor bolts, of the type shown in Figure 4c, are a good example of details conceived for easy inspection and repair. All anchor bolts must be checked after an earthquake and usually a large number of them require re-tightening. It is difficult to imagine, and it has happened more than once, the problems of repairing bolts that are found to be broken, somewhere under the base plate and inside the concrete mass.

It can be concluded that the responsibility of the earthquake engineer on industrial projects is not limited, as in other assignments, to the design of main structures. He also must, together w' with process engineers and the operators, visualize all other possible effects of the earthquake in order to minimize indirect losses due to failure of essential services or prolonged shutdowns.

13. CONCLUSIONS AND RECOMMENDATIONS

Main features of Chilean seismic-design practice in major industries have been reviewed. Even though conclusions are given in the text, the main ones are summarized below:

- one of the most important factors in good seismic design is the establishment of early and adequate coordination between the earthquake engineers and the process, mechanical, electrical and civil designers;

- seismic design specifications should be prepared for every project and made a part of the bidding documents of main equipment. It is generally an error to rely on standard building code requirements;

- design specifications should clearly list the units and equipments that require special treatment and dynamic analysis;

- earthquake engineers must review and approve drawings of all equipment and secondary structures, no matter how small or irrelevant they may appear;

- details should be designed for easy inspection and maintenance; and

- design provisions to maintain essential services and to minimize shutdowns should be considered to be of prime importance and jointly established by a team of earthquake, process and operating specialists.

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Table 1

Seismic Coefficients a/g for static Design

Structure	Seismic Zone Normal	Low
Steel or Reinforced Concrete Buildings	0,15	0,10-0,12
Bins, Silos, Tanks	0,20	0,15
Stacks, Tall Vessels	0,20	0,15
Heavy Equipment and Connections	0,30	0,20
Walls, normal to their plane	0,20	0,15
Cantilevers and Parapets	1,00	0,70
Vertical Earthquake, when required	50% of horizontal	

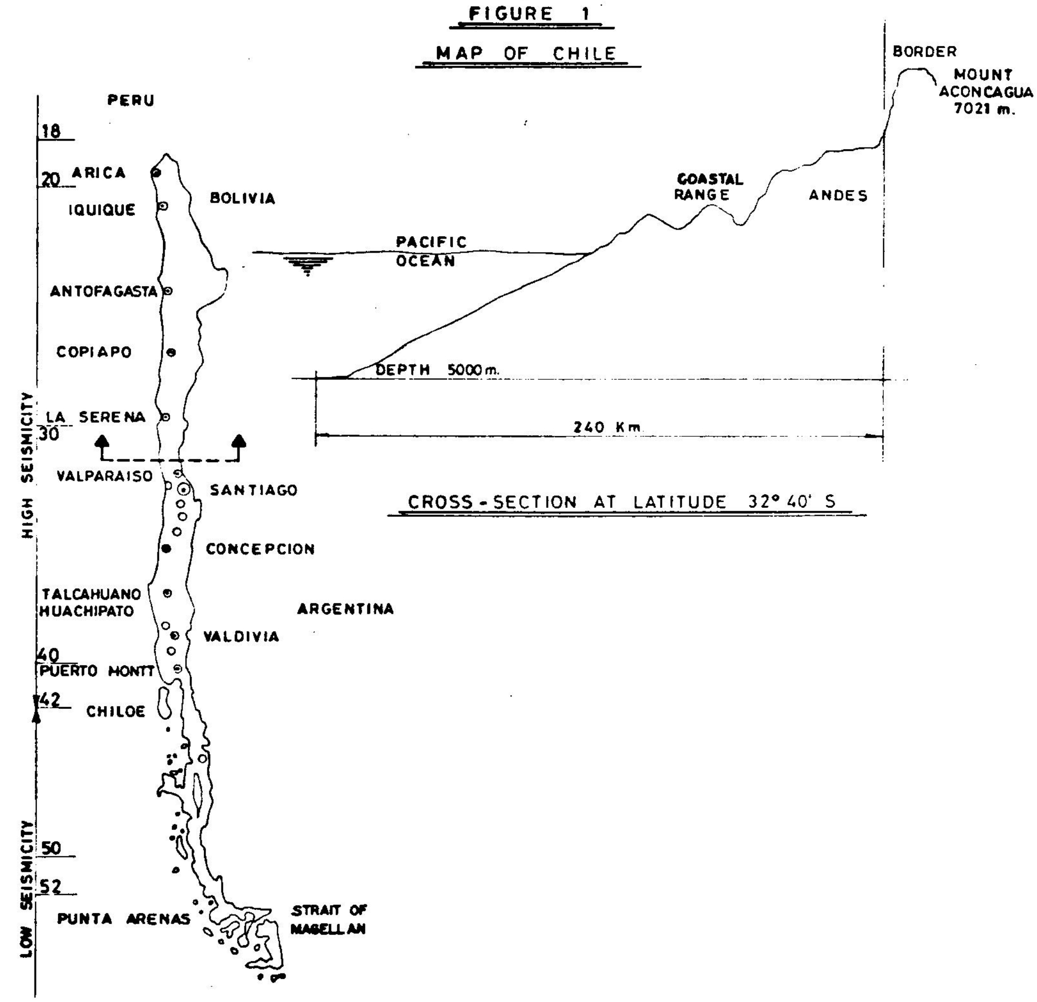
Table 2

Seismic Live Loads

Description	Seismic LL/Normal LL. Ratio
Passageways, Ladders, Crane Platforms, Roofs	0
Maintenance Platforms	0,25
Operating Floors, Machine Room Floors, Furnace Loading and Unloading Floors	0,25
Rolling Mill, Continuos Casting or Pouring Floors	0,50
Paper and Pulp Mill Warehouses	0,50
Transit and General Warehouses, Docks, Piers, Wharves	0,50
Heavy-industry Warehouses, Repair and Maintenance Floors	0,80

FIGURE 1

MAP OF CHILE



CROSS-SECTION AT LATITUDE 32° 40' S

FIGURE 2 ACCELERATION AND DESIGN SPECTRA

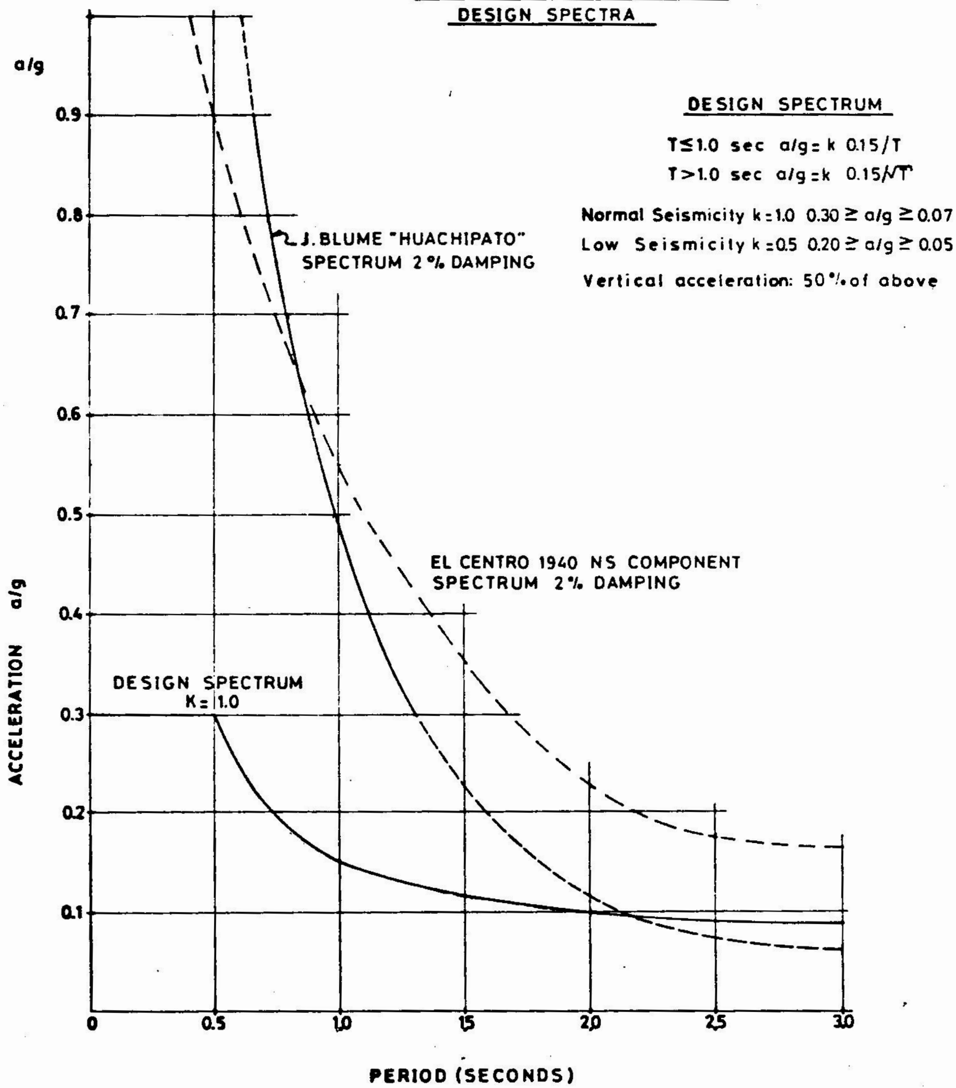
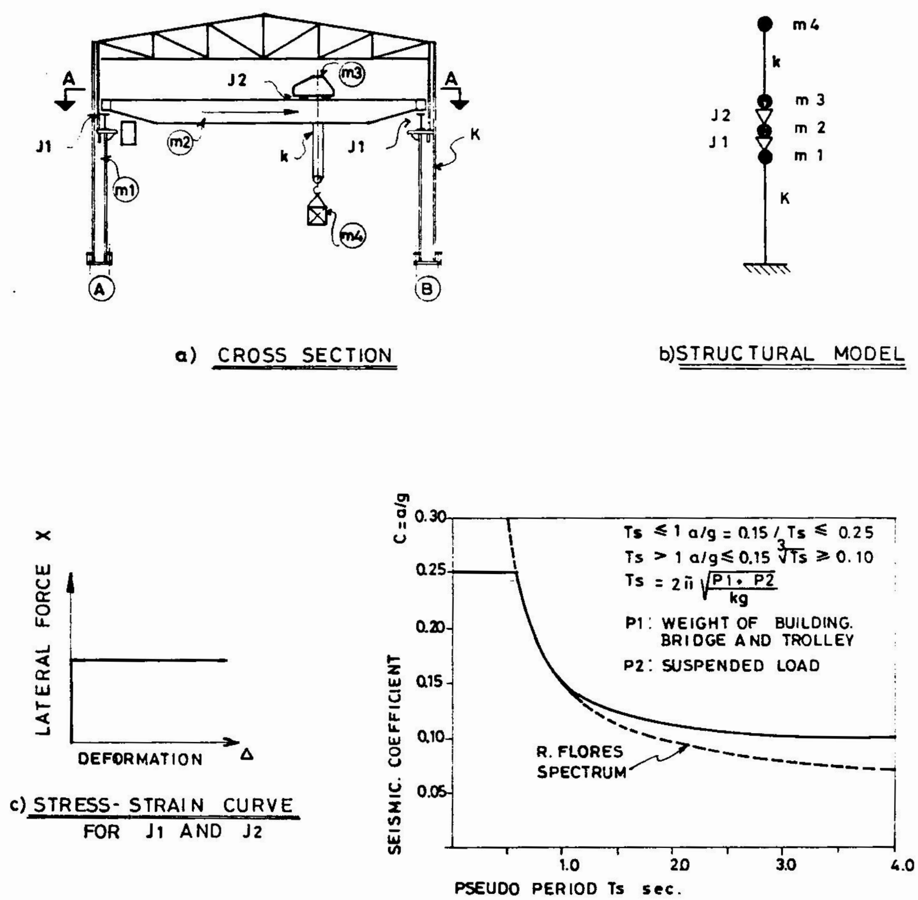


FIGURE 3

MILL BUILDINGS



a) CROSS SECTION

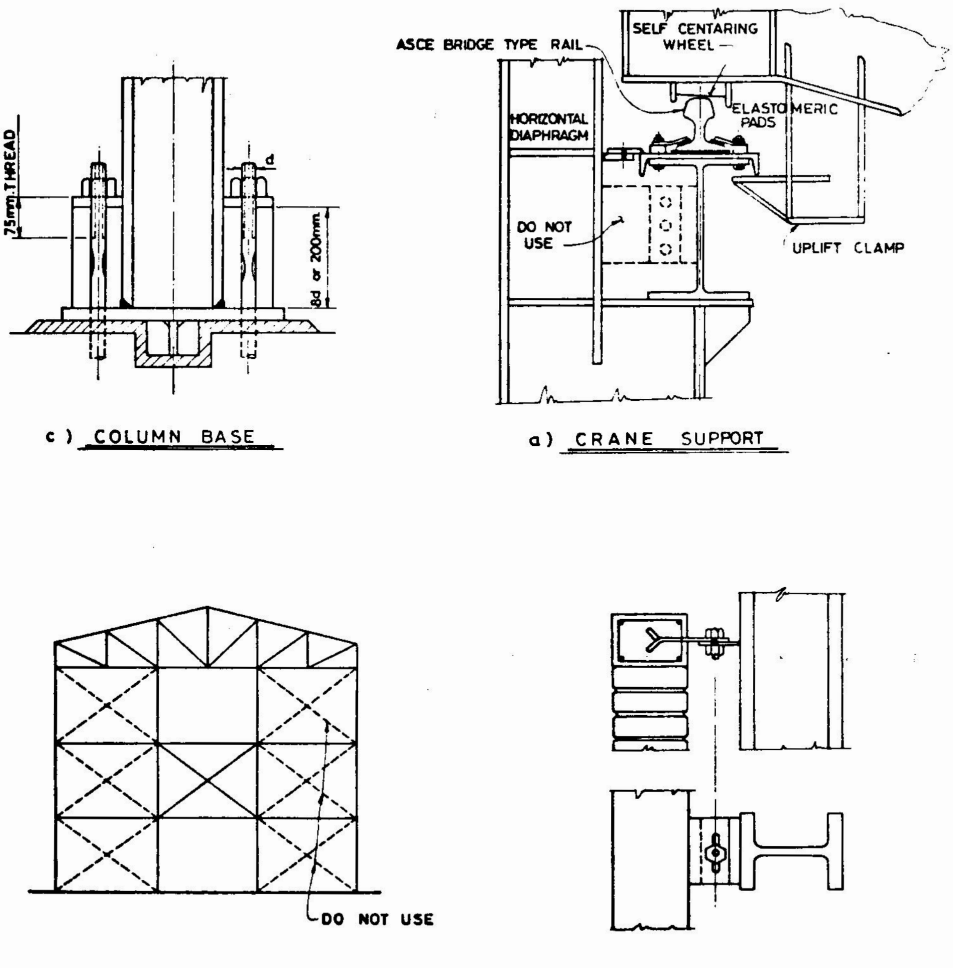
b) STRUCTURAL MODEL

c) STRESS-STRAIN CURVE FOR J1 AND J2

d) DESIGN SPECTRUM

FIGURE 4

MILL BUILDING DETAILS



c) COLUMN BASE

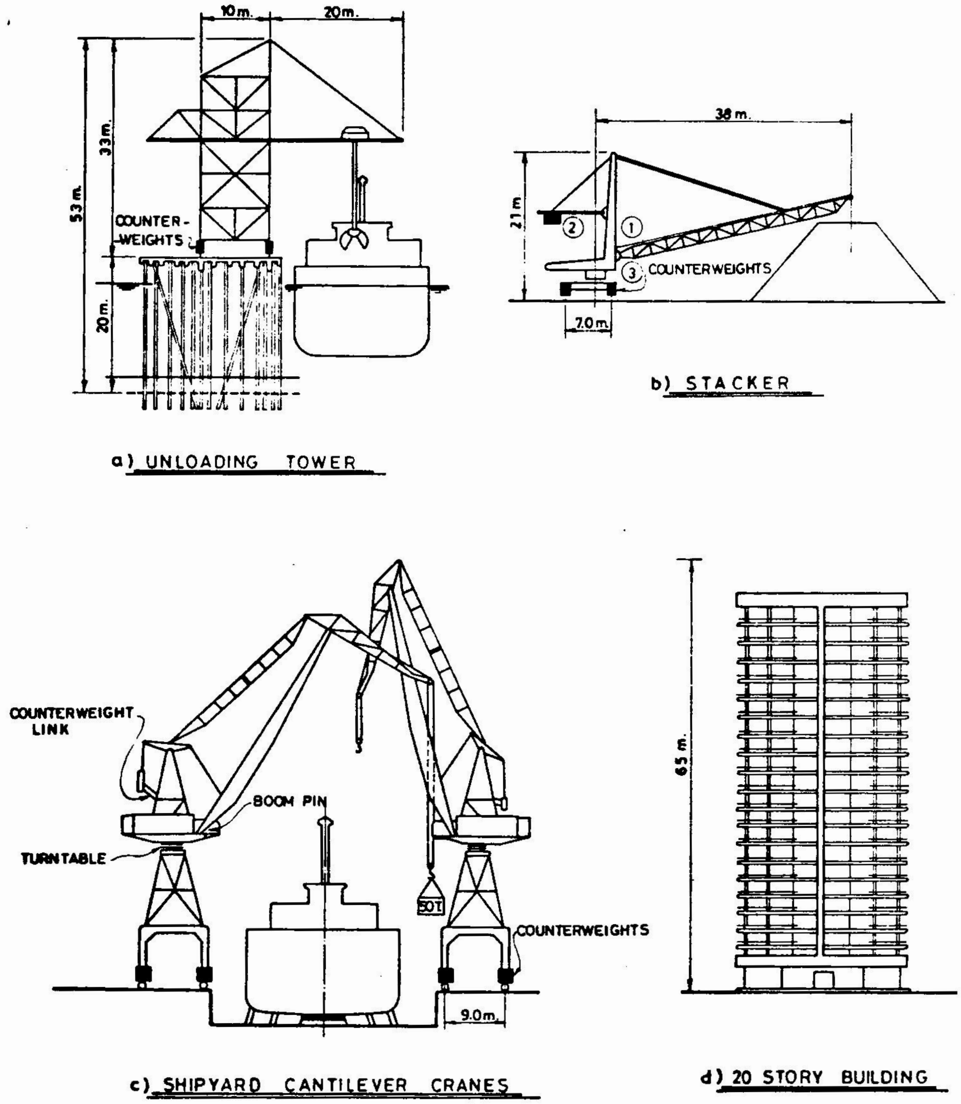
a) CRANE SUPPORT

d) END WALL BRACING

b) MASONRY WALL CONNECTION

FIGURE 5

LARGE MOBILE EQUIPMENT



a) UNLOADING TOWER

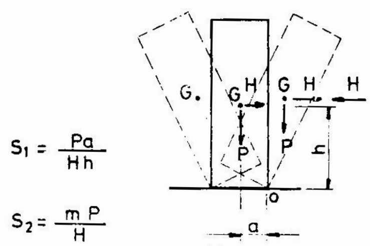
b) STACKER

c) SHIPYARD CANTILEVER CRANES

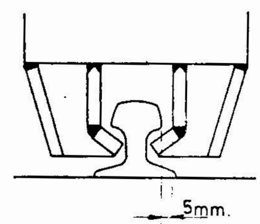
d) 20 STORY BUILDING

FIGURE 6

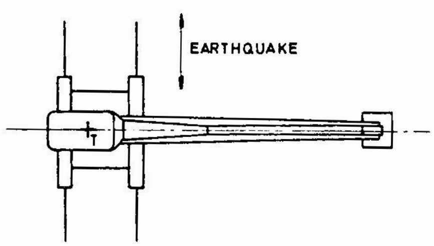
LARGE MOBILE EQUIPMENT



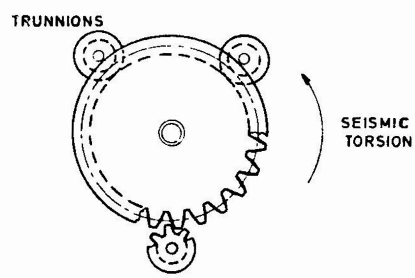
a) ROCKING



b) UPLIFT ANCHOR



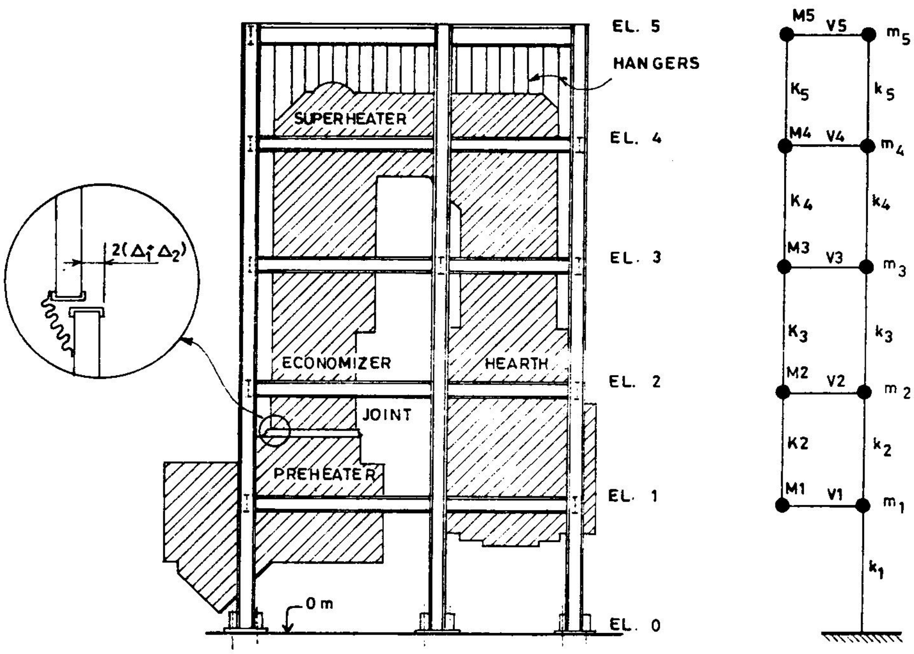
c) HORIZONTAL TORSION



d) TURNTABLE MECHANISM

FIGURE 7

HEAVY HANGING EQUIPMENT

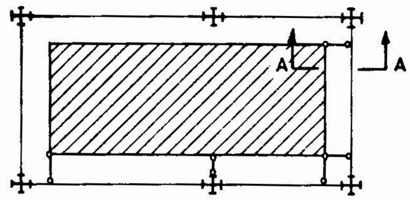


a) ELEVATION

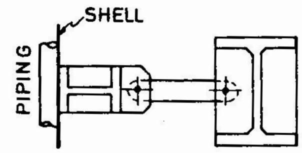
b) STRUCTURAL MODEL

FIGURE 8

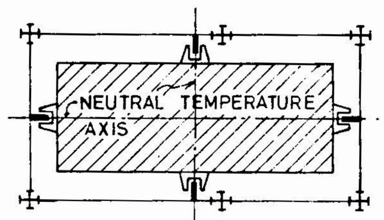
HEAVY HANGING EQUIPMENT

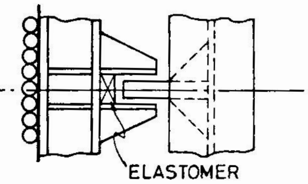


a) EARTHQUAKE TIE BARS

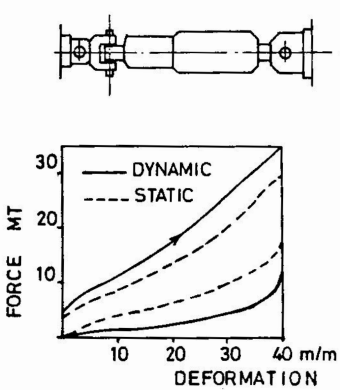


SECTION A-A

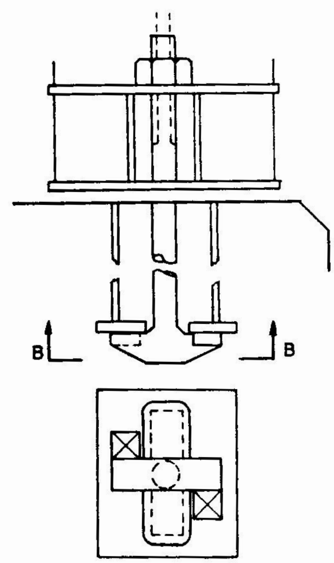




b) EARTHQUAKE GUIDES



c) EARTHQUAKE DAMPERS

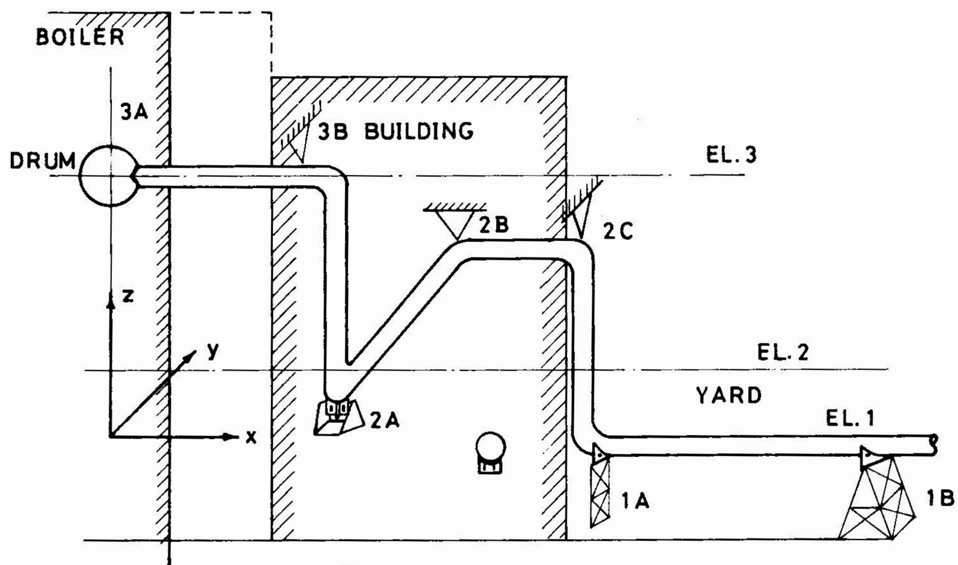


SECTION B-B

HAMMERHEAD BOLT

FIGURE 9

PIPING



ELEVATION	SUPPORT	DIRECTION FIXED	MOVABLE
3	A	x. y. z	–
	B	y. z	x
2	A	x . y	z
	B	x. z	y
	C	y. z	x
1	A	y	x . z.
	B	x. y. z	–

FIGURE 10

TALL SLENDER STRUCTURES

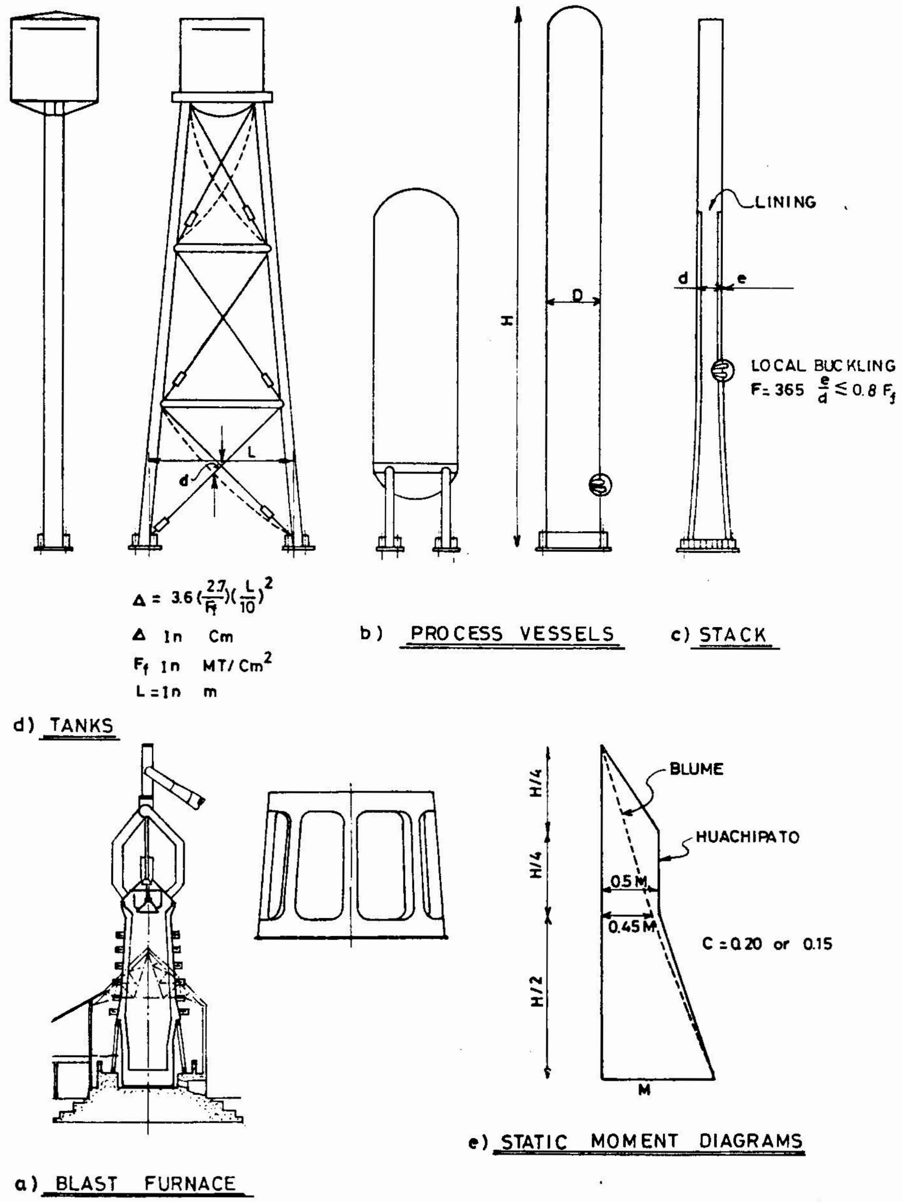
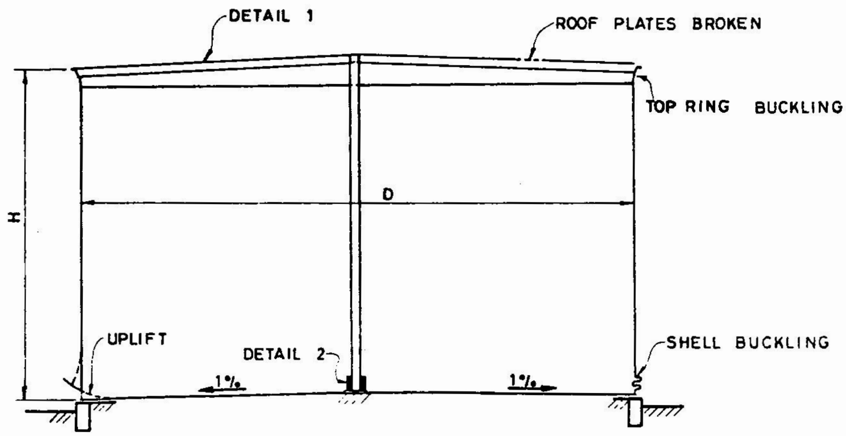


FIGURE 11

FIELD STORAGE TANK



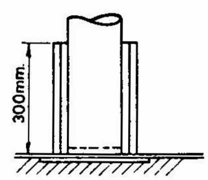
$$e \geqslant H\frac{\sqrt{C D p}}{27}$$

e in cm.
h - D in m.
p in T/M^3

a) OIL TANK

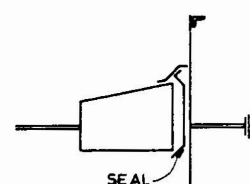
b) DETAIL 1

ROOF PLATES



c) DETAIL 2

COLUMN SUPPORT

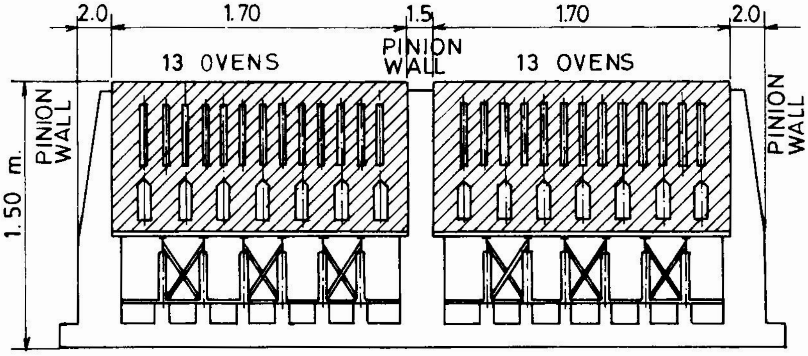


d) DETAIL 3

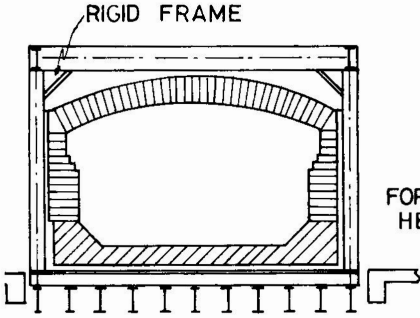
FLOATING ROOF SEAL

FIGURE 12

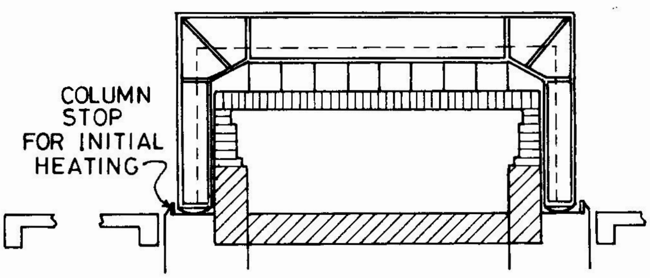
INDUSTRIAL MASONRIES



HUACHIPATO COKE OVENS



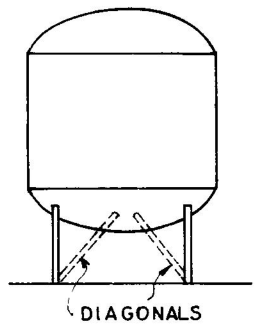
b.) ARC ROOF



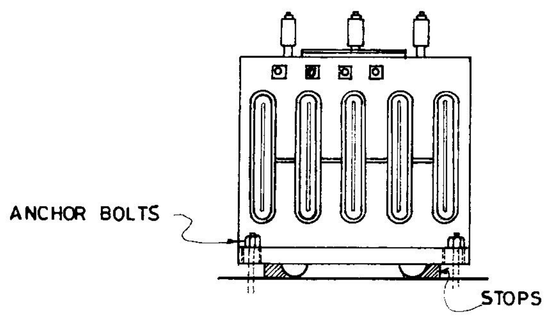
c) SUSPENDED ROOF

FIGURE 13

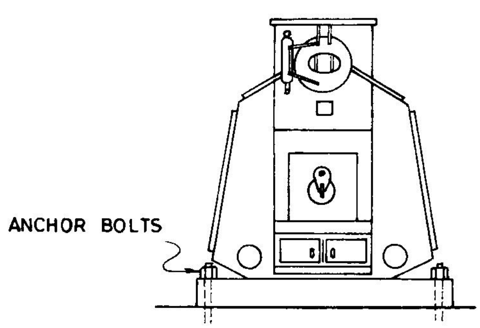
SECONDARY STRUCTURES



a) PRESURE FILTER



b) TRANSFORMER



c) PACKAGE BOILER