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Seismic retrofitting of oil refinery equipment

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ABSTRACT: This paper describes a seismic evaluation and retrofitting program implemented in a plant which is part of a major oil refinery located in a high risk seismic region of Venezuela. The Alkylation Plant has a significant number of horizontal and vertical vessels and towers which were designed more than thirty years ago, when earthquake specifications were less demanding than the ones in use today. After a detailed seismic evaluation, the following critical zones were identified: skirt and anchor bolts in vertical vessels; saddles and support structure for horizontal vessels; anchor bolts and reinforced concrete columns for a cracking tower. As a result of the program, four vertical and three horizontal vessels, as well as a cracking tower, were reinforced in order to increase their seismic reliability.

1 INTRODUCTION

Past earthquakes have caused damages in oil installations located around the world. Typical damage consists of buckling of tanks, ruptures of pipes and failures in anchor bolts for vessel supports. Cylindrical steel tanks supported directly on the ground have been particularly affected. A tank damage summary for 13 earthquakes that ocurred in the world during the 1964 - 1987 period, with Richter magnitudes between 6.2 and 8.4, show 84 tanks with severe damage or collapse and 88 tanks with intermediate or minor damage, out of a total of 549 tanks that were exposed to seismic ground motions in the epicentral areas (Grases et al, 1990).

Oil refineries built some decades ago are of major concern to managers and engineers since seismic actions and design criteria have changed rapidly in recent years. A good example is the Recope Refinery that was exposed to severe ground motion (40 km from the epicenter) during the Costa Rica earthquake (M_S = 7.4) on April 22, 1991 (López et al 1991). Most of the refinery installations were built in 1964; furthermore, the refinery is located in an area (Atlantic coast) which was considered to represent a moderate seismic hazard in comparison with other regions (Pacific coast) in the country. As a consequence of the shaking, the refinery was out of operation for several months. Major damage consisted of pipes fractured at joints, brittle failure of bolts in vessel foundations and buckling of tank walls and roofs. Out of a total of 40 atmospheric storage tanks, 15 had some degree of damage. In particular, one exploded, two burned and five showed considerable oil spilling due to base and/or roof failures. Most tanks (95%) were not anchored to the foundation.

This paper describes a seismic evaluation and retrofitting program implemented at a plant which is part of a major oil refinery located in a high risk seismic region of Venezuela. The refinery is located in the north-eastern part of the country, in a region which has been affected by large magnitude events. The Alkylation Plant has several horizontal and vertical vessels and towers that were designed more than thirty years ago (Figure 1) based on seismic requirements that differed substantially from those currently in use for new installations. Furthermore, given that some vessels contain high risk materials, they require special protect in order to minimize the possibility of failure during severe earthquakes.

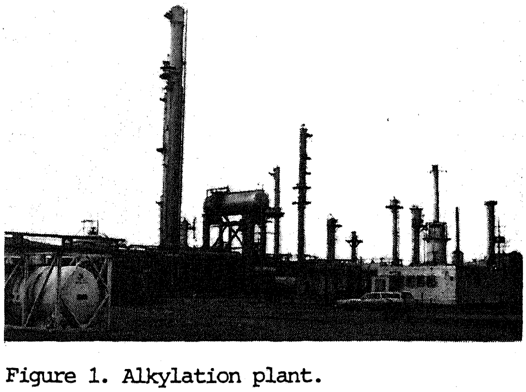

Figure 1. Alkylation plant.

2 SEISMIC HAZARD AND RESPONSE SPECTRUM

The seismic hazard was determined by means of a probabilistic model that considers uncertainties associated with the occurrence of events and the propagation of waves. As a result, a 0.27 g peak rock acceleration was determined for a 5% of excedence in 25 years (INTEVEP 1990). From a dynamic response analysis of the soil deposit using a family of simulated rock accelerograms, a 0.54 g mean peak surface acceleration was determined. The resulting mean surface spectrum shows the typical features of a narrow band process with a strong amplification at the 0.2 seconds period (Figure 2). The surface spectrum was smoothed and enlarged in the short period range, based on the observation of typical shapes of registered motions for similar soil conditions. The resulting spectrum (Figure 2) which is consistent with analytical results and registered data, was considered to be representative of the expected horizontal ground motions at the site and therefore was used for the seismic evaluation program. Based on a statistical analysis of recorded accelerograms in Venezuela, the vertical response spectrum was taken as 0.70 times the horizontal spectrum.

3 SEISMIC EVALUATION PROCEDURES

The seismic evaluation procedure can be summarized as follows: i) Selection of critical equipment as a function of direct and indirect consequences of inadequate seismic behavior; ii) Construction of mathematical models of each piece of equipment. Special effects, such as soil-structure interaction and stiffness contribution of pipes, were evaluated; iii) Dynamic response analysis and combination with other actions, such as gravity loads, internal pressure and temperature; iv) Determination of the strength and ductility capacity of system and critical members; v) Calculation of a failure index for each critical region; it is defined as a ratio between seismic action and resistance.

3.1 Dynamic Properties

Each piece of equipment, including the support structure, was modeled as a space structural system with three translational degrees of freedom per lumped mass. The most significant properties of vertical vessels and towers are presented in Table 1. The catalytic reactor (RC) is a 53 meter tall tower with 16 Ø 1" bolts anchored to a reinforced concrete structure. A fundamental period of 0.83 sec was measured by means of ambient vibration techniques (INTEVEP 1990); the calculated period was 0.91 sec, reasonably close to the experimental value. Damping values vary between 1% and 4% for the first four vibration modes. Soil-structure interaction effects on fundamental period was evaluated for all vertical vessels. A parametric study done with data for eight vertical vessels indicated that interaction increased with vessel diameter and decreased with slenderness ratio. The largest influence was found for the RC tower where the fundamental period increased 15%.

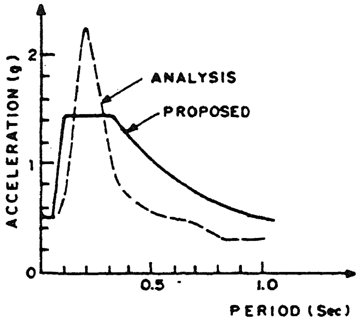

Figure 2. Response spectrum.

Table 1. Vertical vessels and towers

Name	Description	Height h(m)	Diameter D(m)	Operating Weight (tons)	Period T_1 (sec)
T1	Vessel on skirt with a base ring bolted to the foundation	31	0.95	31	1.44
T2	" "	55	3.12	294	1.30
T3	" "	13	0.79	12	0.39
T4	" "	26	1.10	26	1.09
T6	Vessel on skirt supported on four steel leg columns	6.6	0.77	7	0.43
RC	Tower supported on four reinforced concrete columns	53	4.70	499	0.91

Table 2. Horizontal vessels

Name	Description	Height (m)	Operating Weight (tons)	Fundamental Period		
				Longitudinal		Transversal
				Fix	Roller	Fix/roller
D4	Drum on saddles supported on reinforced concrete walls	5.3	106	0.10	0.14	0.08
D7	Drum on saddles supported on a braced frame	17.6	226	0.24 *	0.24 *	0.25 *
D8	" "	7.6	100	0.17	0.17	0.24

* : When pipe stiffness is included, periods decreased 13%.

With the data shown in Table 1 and additional data not reported here, it was found that the formula $T_1 = 0.042\ h/\sqrt{D}$ gives a good aproximation to the fundamental period, especially for vessels supported directly of the ground; h is total height and D is mean diameter, in meters.

The principal characteristics of the horizontal vessels are shown in Table 2. Fundamental periods are indicated for both longitudinal (drum axis) and transversal directions;

several models were analyzed in order to evaluate the effects of free movement at one support (roller) and pipe stiffness.
As shown in Table 2, the type of assumed support is significant only for vessel D4, while pipe stiffness is important in vessel D7. Damping in all modes was assumed to be 3% of critical for all systems.

3.2 Seismic responses, structural capacities and failure indexes.

The maximum dynamic response was obtained for each piece of equipment considering the simultaneous action of the three ortogonal spectrum components, combined according to the standard SRSS combination criteria. For each seismic component, the maximum modal responses are combined using the complete quadratic combination criteria. The number of modes included in the analysis is such that the contributing mass for all modes is greater than 0.90 times the total mass of the system. Seismic response is combined further with gravity and internal pressure.

Reduction factors are applied to the member seismic forces in order to account for energy dissipation capacity in the inelastic range. A factor of 1.5 was used for anchor bolts of vertical vessels and for reinforced concrete columns and shear walls, 2.5 for reinforced concrete beams and 2.0 for foundations. No reduction was allowed for skirts, vessel walls and saddles of horizontal vessels.

Structural capacity of reinforced concrete members was determined at ultimate limit states according to national standards (equivalent to ACI 318-83). For steel members capacities are defined in terms of allowed stresses (equivalent to AISC standards); in this case, seismic action is reduced accordingly to a service stress level.

Failure indexes at critical regions are defined as the ratio between net acting stresses and member capacities. Table 3 shows failure indexes at critical regions for each piece of equipment. Values greater than one mean that acting stresses exceed actual capacity in that region. Values for vessel walls are always less than one and are not shown in the Table. Skirts are the critical zones of vertical vessels because failure indexes greater than one are associated with local buckling. The fundamental period is the system parameter that most influences the severity of seismic effects. The short periods of vertical vessels T3 and T6 (Table 1) are in the period range of maximum seismic energy (Figure 2), and therefore have the larger failure indexes. On the other hand, since vessel T1 has the largest period (1.44 sec) and is located in the descending branch of the response spectrum, its failure indexes are less than one. Vertical vessel T6 shows large failure indexes in the supporting structure, which consists of four steel columns (L 3" x 3" x 1/4") separated by only 50 cm; failure indexes greater than one are associated to tensile and shear force.

Table 3. Failure indexes

Equipment	Skirt	Anchor bolts	Saddles	Support structure
T1	0.8	0.9	-	-
T2	1.8	1.2	-	-
T3.	2.1	2.8	-	-
T4	1.4	1.0	-	-
T6	-	10	-	10
RC	1.0	2.0	-	1.5
D4	-	-	5	2.1
D7	-	-	21	1.5
D8	-	-	20	4.1

All horizontal vessels have indexes greater than one in the saddles that connect the drums to the supporting structure. Anchor bolts in the short direction of saddles do not have the capacity to transfer shear and bending forces. Also, the supporting structures show indexes greater than one in the columns (D7 and D8) and in the short dimension of the shear walls (D4).

Some foundations show some upraising due to overturning moments. It was decided to allow an upraising of no more than 25% of the total area of the plate.

4 SEISMIC RETROFITTING OF EQUIPMENT

The retrofitting criteria adopted for vertical vessels was the following: i) to allow energy dissipation by means of inelastic deformation of anchor bolts, and ii) to assure elastic behavior of skirts so that brittle failure is not possible. Skirts for vessels T2,T3 and T4 were reinforced to reduce failure indexes below one. Although anchor bolts for vessels T2 and T4 show indexes slightly greater than one, it was decided not to reinforce them in order to take advantage of its redundancy and inelastic deformation capacity (actual free length of bolts is 30 cm). Skirts were reinforced by means of welding steel beams in longitudinal and circumferential directions in order to increase local buckling capacity and section inertia so that seismic axial stresses are also reduced. Vessel T1 was not reinforced.

The anchor bolt system that connects the skirt to the concrete foundation in vessel T3, was reinforced to increase overturning moment resistance and to introduce additional redundancy and energy dissipation capacity. Existing bolts are 8Ø1", with an estimated yield stress of 1700 kg/cm^2. The reinforcement criteria was to add 8 new A307 bolts (yield

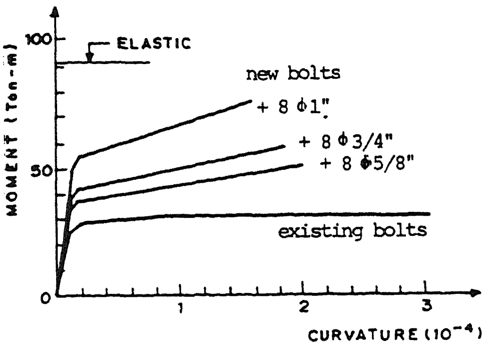

Figure 3. Bolt reinforcement for vessel T3.

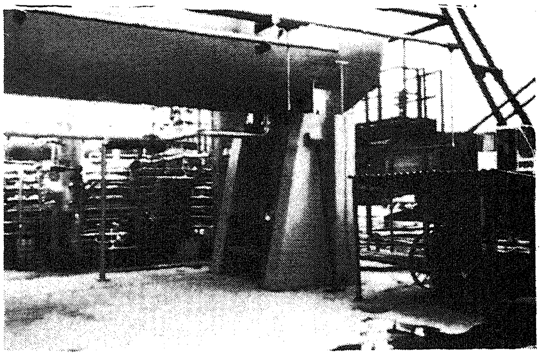

Figure 4. Reinforcement for vessel D4.

stress of 2800 kg/cm^2) with a free length of one meter. Several reinforcing alternatives were evaluated, varying the bolt diameter. An inelastic analysis of the base was performed to study the bolt diameter influence. Annular ring is 20 cm wide. Bolt circle radius is 55 cm. The results of the analysis are given in Figure 3; maximum curvature is defined by a 0.002 maximum concrete strain. Increasing bolt diameter increases overturning moment resistance and decreases curvature deformation capacity. The adopted diameter is 5/8", which yields a ductility demand on the order of 2.3; this value seems appropriate for the new highly redundant system (16 anchor bolts). A larger resistance does not seem adequate since the main objective is to protect the skirt in order to reduce the probability of a catastrophic failure of the whole system.

Given the large failure indexes obtained, the supporting structure and foundation of vessel T6 were replaced by a new one. The new structure consists of four square (25 cm side) reinforced concrete columns with four longitudinal N° 6 and Ø3/8" transversal steel bars each 6 cm. The top of each column ends in four vertical steel plates welded to the vessel walls. At the bottom, each column is fully anchored to the new foundation. Due to the redundancy of the support structure, a ductility factor of two was adopted for design.

The catalytic reactor RC was reinforced to increase resistance and the energy dissipation capacity of the anchor bolts and of the reinforced concrete support structure. 20 new N° 14 (A42) bolts were located between the existing 20 N°16 bolts, around a new annular ring welded to the existing one. New bolts go across the octogonal beam that supports the annular ring and are fixed at the bottom; therefore the bolts have a free length of 120 cm and are capable of absorbing and dissipating large amounts of energy. The concrete columns were confined by 1/2" steel plates all around their perimeter; these plates are welded to the top beam and bolted to the foundation.

All the horizontal vessels were reinforced for the purpose of increasing the resistance of the support structures and saddles that support the drums. Two transversal shear walls were added to the existing walls in vessel D4 in order to resist overturning in the drum axis direction. The saddles were reinforced in their short dimension (drum axis) by means of steel plates and stiffeners that are bolted at the bottom to the new shear walls and are welded at the top to the drum wall (Figure 4).

The saddles of vessels D7 and D8 were strengthed in their short dimension with stiffener welded to a system of plates that confine the support concrete beams. All concrete columns were confined by steel beams that were welded to the beam plates and bolted to the foundation.

5 CONCLUSIONS

The seismic evaluation program applied to a plant built 30 years ago, that is part of a major oil refinery in Venezuela, identified a group of horizontal and vertical vessels that do not have adequate capacity to withstand the expected ground motion at the site. Retrofitting measures that were applied allow for energy dissipation in anchor bolts and supporting structures but assure elastic behavior of skirts, saddles and thin-walled drums. As a result of the program the seismic reliability of the plant was improved considerably.

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