Softening instead of strengthening for seismic rehabilitation

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Softening Instead of Strengthening for Seismic Rehabilitation

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Summary

When rehabilitating existing structures for seismic loading, many engineers would first think of a strengthening approach. However, for the case of the large liquid gas tank described in this paper, it was more effective to soften the structure by shifting the fundamental frequency in the lower spectral region of the response spectrum of the seismic design event. As part of this softening approach, 26 high-damping elastomeric bearings were incorporated into the structural system. These rubber bearings are horizontally soft, which results in a decrease of the fundamental frequency from 2.3 Hz to 0.5 Hz. The drastic reduction in the seismic forces was confirmed by non-linear dynamic analyses in the time domain considering the hysteretic behaviour of the bearings.

Deficient Existing Structures

Over 90% of existing structures in Switzerland were designed without adequate consideration of earthquakes. They possess an unknown, but presumably often insufficient, seismic safety factor. Many of these structures would collapse under a moderate earthquake, which could result in considerable damage to the environment if hazardous materials were released. Certain chemical plants belong to this group of structures. It is in the interests of the owners of these facilities and of the general public that these risks are understood and that the necessary actions are taken to prevent serious problems.

A risk assessment of an existing chemical plant in Switzerland showed that several structures designed and built in the 1970s and 1980s do not comply with current seismic requirements. The seismic rehabilitation of a large tank used to store up to 1000 t liquid gas (Fig. 1) is presented here.

Large Tank for Liquid Gas

The steel vessel is double walled, has a diameter of 15 m and a height of 16 m, and contains equipment to cool the gas down to −30 °C. The vessel is supported by a reinforced concrete structure consisting of a 0.5-m-thick octagonal slab with 26 columns, 2.5 m in height. The columns are supported by 13-m-long drilled piles. An additional steel structure holds a stair tower and the piping that is needed for operation.

The tank is located in an area of moderate seismicity comparable to zone 2 of the Uniform Building Code [1]. A comprehensive evaluation for the design earthquake showed that, in their existing states, the reinforced concrete columns and piles would be vastly overstressed by horizontal forces (which produce bending moment and shear forces) and by the overturning moment (which produces axial forces). In addition, the construction details were not very ductile. Therefore, if the reinforced concrete structure were subjected to a significant earthquake, it would fail, the steel vessel could rupture, and liquid gas could be released into the environment with disastrous effects.

Seismic Rehabilitation

For the seismic rehabilitation of existing structures, the following strategies can be envisaged:

- strengthening for more resistance
- enhancing ductility for more energy dissipation capacity
- stiffening, by shifting the relevant eigenfrequency in the high frequency domain of the design spectrum (as a consequence, the spectral values for the acceleration, displacements and deformations are reduced)
- softening, by shifting the relevant eigenfrequency in the low frequency domain of the response spectrum (as a consequence, the spectral value for the acceleration is reduced, but those for displacements and deformations are increased)

- increasing the damping in order to reduce the spectral values of the acceleration, displacements and deformations.

Many engineers see earthquake action as a set of forces acting on the structure (lateral force method), and for seismic rehabilitation they think primarily of strengthening the structure to provide more resistance. This corresponds to static thinking. However, the rapid back and forth movements of the soil during an earthquake cause a dynamic response of the structures, thereby requiring dynamic thinking.

For the tank discussed here, a strengthening approach would have been possible by adding bracing or structural walls, and additional foundations. This approach, however, has the following disadvantages. The fundamental frequency would still have been in the domain of maximum amplification of the acceleration response spectrum, resulting in high seismic forces. In addition, the risk of failure of the steel vessel (bursting after elephant foot buckling) would not have been reduced.

A much better and more economical solution was adopted, namely seismic isolation, whereby special rubber
bearings were incorporated into the columns. The bearings are horizontally soft and possess high damping characteristics. Thus, the applied strategy for seismic rehabilitation was, in effect, a softening of the structural system. The relevant first eigenfrequency was decreased, thereby reducing the corresponding spectral value of the acceleration. The frequency shift, together with a considerable increase in damping, dramatically reduced the seismic forces and the risk of failure of the steel vessel.

In the sense of a limit state, the behaviour of the isolated tank during an earthquake can be described as follows. Due to the horizontally soft bearings and the mass inertia, the tank and its contents remain in almost the same position, while the soil moves back and forth quickly. The columns are only stressed by the minor restoring forces of the bearings and, because of the high damping, the displacements remain small.

**Ambient Vibration Tests**

It is often difficult to estimate the dynamic properties (eigenfrequencies, eigenmodes, damping) of a structure by calculations. In this example, the relatively soft subsoil added additional uncertainties. As a minimum, the values for the fundamental mode were required to calibrate the analysis models. For this reason, ambient vibration tests were performed. At 40 locations throughout the structure, one of which was located at the soil, the vibrations induced by ambient sources (e.g. wind, traffic, microtremors) were measured by very sensitive acceleration sensors. The first five eigenmodes, with eigenfrequencies between 3.8 Hz and 6.1 Hz, were obtained for the tank containing 160 t liquid gas. These frequencies characterise the dynamic behaviour of the tank for very small amplitudes. They can be considered as upper boundaries for dynamic behaviour during seismic excitation, when a reduction in stiffness is expected due to cracking and plastic deformations. The damping ratio could not be determined for this tank, but for a similar tank structure in the vicinity a damping ratio of approximately 2% was measured for the fundamental mode. The damping ratio was measured for very small amplitudes and represents a lower bound for the damping to be expected during seismic excitation. A value of 2% was assumed for the damping ratio in the calculations.

**Influence of Site Conditions**

It is generally agreed that local site conditions should be considered when determining the seismic behaviour of important buildings [2, 3].

The tank is located in a glacial, originally U-shaped valley, which was filled by ground moraine and later by alluvial and lake deposits up to a thickness of 100–200 m. The shear wave velocity of the soil is about 300–400 m/s in the uppermost 40 m.

An important factor with regard to seismic behaviour is the fundamental frequency of the subsoil. In particular, when a frequency shift is desired for the rehabilitation strategy, it has to be ensured that the rehabilitated structure will not resonate with the shaking ground. The fundamental frequency of the subsoil near the tank was estimated as 1.5 Hz by the Nakamura method, which consists of ambient noise recordings and subsequent calculation of horizontal/vertical spectral ratios [4]. A simple numerical verification with a shear beam model for the soil produced a similar value for the fundamental frequency. Accordingly, the site-specific response spectrum was derived from the spectrum given in [5] for medium-stiff soil of zone 3b by shifting the corner frequency from 2 Hz to 1.2 Hz (Fig. 2) and leaving the amplification factor of the constant acceleration branch unchanged. The relative displacements increase greatly for a shift in the lower frequency domain.

**Seismic Isolation Bearings**

Much progress has been made recently with seismic isolation bearings, particularly multilayer elastomeric bearings (Fig. 3). The geometric properties and the chemical composition of the elastomer can be varied within relatively large limits. Consequently, the stiffness, the desired hysteretic behaviour, and the corresponding equivalent damping can be adapted easily to the requirements of the dynamic analysis.

The idealised hysteretic law of the bearings is shown in Fig. 4, where \( H \) represents horizontal force, \( x \) horizontal displacement, \( k_1 \) initial stiffness, \( k_2 \) tangential stiffness, and \( k \) secant stiffness.

In the preliminary design, the sum of the vertical forces on a bearing due to permanent loads and to the design seismic action (overturning moment and vertical excitation) is determined by a linear dynamic calculation. The surface area of the bearing is selected such that the vertical pressure under these forces does not exceed a reference value (generally 6–8 N/mm²) specified by the bearing manufacturer. Then, the necessary height of the bearing (or the total thickness of the elastomeric layers) is controlled by the deformation behaviour under the hori-
zontal forces. At a shear deformation of 100% of the elastomeric layers, \( k \) corresponds to the stiffness of a linear single-degree-of-freedom system for the design seismic event \( (H = H_{\text{max}} \) and \( x = x_{\text{max}}) \).

For the non-linear dynamic analysis, \( k_1 \) and \( k_2 \) were assumed such that the resulting equivalent viscous damping ratio (\( \zeta \)) agreed as closely as possible with the real bearing behaviour according to [6]:

\[
\zeta = \frac{1}{4 \times \text{strain energy at maximum displacement}}
\]

The dissipated energy of one cycle corresponds to the area enclosed by the force-versus-displacement hysteresis curve.

**Design Criteria**

The design and dimensioning followed the relevant Swiss standards. Because of the high potential for environmental damage, the structure was assigned to the highest importance category, where a fully elastic response is required under the site-specific seismic design event. In addition, overstrength was neglected whenever this was on the safe side. For the damping in the dynamic calculations of the final design, the following values were assumed:

- \( \zeta = 5\% \) for analysis of the existing state (on the unsafe side, with an estimated 2\% for the structure and practically no dissipative non-structural elements)
- \( \zeta = 5\% \) for analysis of the rehabilitated state (on the safe side, with \( \zeta = 8\% \) for the bearings and \( \zeta = 2\% \) for the remainder of the structure)

For further design assumptions, those given in [7] were used.

**Preliminary Design and Dynamic Hand Calculations**

For the dynamic hand calculations of the preliminary design, the tank was modelled as a linear single-degree-of-freedom system with sufficient precision. The full tank with 1000 t liquid was the governing state. The horizontal fundamental frequency of the full tank was estimated from the results of the ambient vibration tests on the nearly empty tank to be 2.2 Hz. To reflect the main concept of the rehabilitation, this frequency was lowered to 0.5 Hz (Fig. 3) by providing seismic isolation bearings at the tops of the columns located immediately below the existing reinforced concrete slab (Fig. 5). A preliminary design resulted in tentative bearing dimensions. These were later revised to a diameter of 300 mm and a height of 165 mm.

The reduction of the seismic forces at the tops of the columns was not sufficient to alleviate the heavily overstressed columns and piles. Therefore, it was proposed to also build a new reinforced concrete slab monolithically connected to the columns below the bearings. This slab reduces the lever arm of the horizontal bearing forces and redistributes the resulting forces due to frame action. It also provides an almost rigid horizontal connection between the 26 columns, thus preventing relative horizontal displacements under seismic action (only synchronous displacements are possible). Furthermore, the slab transmits the forces from the temporary shoring to the columns during the construction stage.

In the preliminary design, the new slab was positioned approximately 1 m below the bearings. In the final design, further optimisations by dynamic calculations allowed a lower position, presenting considerable advantages for the construction of the slab and the accessibility of the bearings (Fig. 5).

Further hand calculations were performed to determine the following: bending and shear in the columns; vertical forces on exterior columns due to overturning moments; vertical forces on columns due to vertical seismic excitation; punching shear between columns and the existing slab; vertical forces on exterior piles due to frame action of the new slab; and bending and shear in the column to new slab connections. As confirmed by the final design, all governing quantities could be estimated by hand during the preliminary design with a precision of 10–20%.

**Dynamic Analyses**

For the final design, a finite element model of the structural system was used for dynamic calculations. Important parameters, such as the stiffness and constitutive law of the bearings, damping, position of the new slab, analysis procedures, etc., were systematically varied and optimised where required. Due to the slenderness of the tank, the convective part of the liquid becomes relatively small. According to the simplified procedure in [8], the sloshing frequency was about half of the new eigenfrequency of 0.5 Hz. Resonance could therefore be excluded. Consequently, sloshing was neglected and the liquid assumed to move rigidly with the tank.

In the first step, the finite element model of the existing state was calibrated to be consistent with the results of the ambient vibration test of the tank with 160 t liquid. The built-in boundary condition of the piles in the rather soft subsoil was fixed at a level that ensured that the fundamental frequencies of the model and the test coincided. The next step was a linear dynamic calculation of the existing state for the full tank using the response spectrum analysis method for \( \zeta = 2\% \). The enormous overstresses found by previous hand calculations were confirmed. The response spec-
trum analysis of the tank with seismic bearings and the new slab ($\xi = 8\%$ for the first eigenmode and $\xi = 2\%$ for the higher eigenmodes) demonstrated the considerable reduction of the stresses. The bearings were modelled as linear, horizontal and vertical spring elements with the secant stiffness. The optimal position of the new slab was found by further response spectrum analyses. As an example of the linear finite element analyses, the fundamental mode shape of the rehabilitated state of the tank with a frequency of 0.5 Hz is shown in Fig. 6.

A non-linear dynamic analysis in the time domain was performed for the optimised system. For modelling of the bearings, elastoplastic spring elements with kinematic hardening were used. The resulting bearing behaviour followed the bilinear hysteretic law of Fig. 5. In the vertical direction, the bearings were modelled as linear spring elements. The damping in the non-linear analysis was produced directly by the hysteretic behaviour of the bearing elements without having to assume an equivalent viscous damping ratio. An artificial ground motion was used as earthquake excitation. It was generated compatible to the site-specific design spectrum with a lower corner frequency of 1.2 Hz. The acceleration and displacement time histories and the acceleration response spectrum of the utilised ground motion are shown in Fig. 7. The calculated time histories of the horizontal relative displacements above and below the bearings, and a typical force versus displacement hysteresis curve for a bearing are shown in Fig. 8. A maximum horizontal bearing displacement of 100 mm was obtained from the non-linear dynamic analysis (Fig. 8), compared with 116 mm from the response spectrum analysis. This confirmed that the simplifying assumptions for stiffness and damping of the linear analyses were on the safe side. The resulting stresses of the non-linear dynamic analyses proved the favourable behaviour of the rehabilitated tank.

Tests of the Bearings

To check the properties of the seismic isolation bearings, acceptance tests were performed. All bearings were loaded three times in the axial direction with the vertical design force.

To allow testing to failure, two additional bearings were fabricated. A pair of randomly selected bearings was subjected to the following tests:
- static cyclic shear test at maximum permanent axial force
- dynamic cyclic shear test with 0.5 Hz at three levels of axial force

**Fig. 7: Ground motion (a) and acceleration (b) spectra for $\xi = 5\%$**

**Fig. 8: Relative horizontal displacement above (solid line) and below (dotted line) the bearings (a) and hysteresis curve of a bearing (b)**

**Fig. 9: Deformation of two bearings during a static failure test**

**Fig. 10: Hysteresis curve of dynamic acceptance tests of the bearings**

- static failure test at maximum design axial force (Fig. 9).

The maximum displacement in dynamic cyclic shear tests at 115% maximum permanent axial force reached ±120 mm (Fig. 10), corresponding to a shear strain of 115% of the elastomeric layers. From the enclosed surface area of the hysteresis curves, $\xi$ was calculated as 11%. The hysteretic law measured in the test agrees well with the hysteretic law assumed in the non-linear dynamic calculations (Fig. 8). The static shear test to failure started with three cycles of increasing displacements of ±150, ±180 and ±210 mm. Failure occurred at a displacement of 240 mm, 2.4-fold higher than the calculated displacement for the design earthquake (102 mm), and the shear strains in the elastomeric layers reached 230%.

Construction Procedure

As the first step of rehabilitation, the new slab, monolithically connected to the existing columns, was poured on a sand gravel bed. After the slab had hardened sufficiently, the columns were rehabilitated four at a time. Two steel columns were mounted on the sides of each reinforced concrete column by means of a hydraulic jack. The slab was then lifted up until the column was no longer loaded, as judged by extensometer measurements. A 24-cm-long strip was cut out at the top
of the column, and the seismic isolation bearings were installed and loaded, by means of flat jacks, to the column force measured at the previous unloading. The steel columns were removed, and the column caps were reinforced and poured (Fig. 11).

**Stair Tower and Piping**

The seismic isolation of the tank leads to small forces but large displacements during an earthquake. The stair tower and the piping, including fastenings, have been designed for an all-round clearance of 200 mm to allow free vibration of all parts without impairing serviceability or structural safety.

**Conclusions**

When rehabilitating an existing structure for seismic action, different strategies should be considered and the most suitable selected. Because structures respond dynamically to earthquakes, the engineer has to think in terms of dynamics. The often-practiced static approach often leads to misconceptions. Depending on the circumstances, softening instead of strengthening may be the better strategy. The softening approach can be realised by incorporating seismic-isolation bearings into the structure. The resulting frequency shift to the lower spectral acceleration domain of the seismic design spectrum drastically reduces the earthquake forces.

**References**


