The influence of foundation conditions on the earthquake response of two tanks

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ABSTRACT: Surface mounted tanks are an important part of the infrastructure. This paper presents the results of analyses of the seismic response of two tanks including the compliance of the foundation soil. The soil – structure interaction is solved in the frequency domain in an approximate strain compatible manner. The method is applied to two typical situations where tanks are employed. One is low lying soft ground adjacent to harbours and rivers. The other involves elevated terrain where the foundation soil is likely to be reasonably competent ground. Significant interaction is found to occur in both cases, but particularly in the case of the soft soil. The translations and rotations of the tanks are shown to be substantial in some situations and greatly effect the forces acting on the tank. Time dependent factors of safety of bearing capacity and shear are presented to investigate the capacity of the foundation to withstand bearing and horizontal shear.

1 INTRODUCTION

Tanks are an important part of the earthquake engineering lifeline network and have been an area of interest in this regard for some time. These facilities are important for fire fighting resources, potable water supply and the provision of oil or gas products. The failure of tanks may lead to loss of water for fire fighting, fires, loss of scarce energy supply and environmental damage. These facilities may be considered a critical link in the seismic lifeline network.

Earthquake induced damage to tanks may take a variety of forms. Tanks may experience

- buckling of the wall and development of a classical elephant-foot shape at the tank bottom
- liquid forces that cause wall and /or roof damage
- base shear that causes the tank to slide
- overturning moment that causes rupture of the wall or mounting frame or foundation failure
- rotations and displacements that cause rupture of connections

Numerous studies, e.g. Housner (1963), Veletsos (1984, 1990), Haroun and Housner (1981) and Veletsos and Tang (1990), have been performed dealing with the hydrodynamics of tanks under earthquake loading. This body of literature has shown that there are two ways in which the liquid moves. Part of the liquid moves in a long period sloshing manner while another part is considered to be rigidly attached to the tank wall. The first mode is known as the convective response and determines the necessary freeboard of the tank while the second is the impulsive response and contributes predominantly to the base shears and overturning moments. Often the convective response is of lesser importance in determining the base shear and overturning moments on the tank wall or the foundation.

The work presented here concerns the effect the ground condition has on the response of a tank and the associated overturning moments and base shears on the foundation. Flexible soil conditions will introduce foundation compliance and change the response of the tank through soil / structure interaction. The method employs an approach intermediate between a simple static short-hand calculation and a sophisticated but expensive finite element simulation or the like. The method described here is considered to be an effective optimisation of design effort.

2 THEORY

The system addressed in this paper is shown in Figure 1. The tank is circular, upright of height H, and is supported on a rigid massless foundation of diameter D at the surface of a homogeneous elastic half space. The tank is assumed fixed to the foundation. The liquid is assumed to be incompressible, inviscid and to have a free surface.

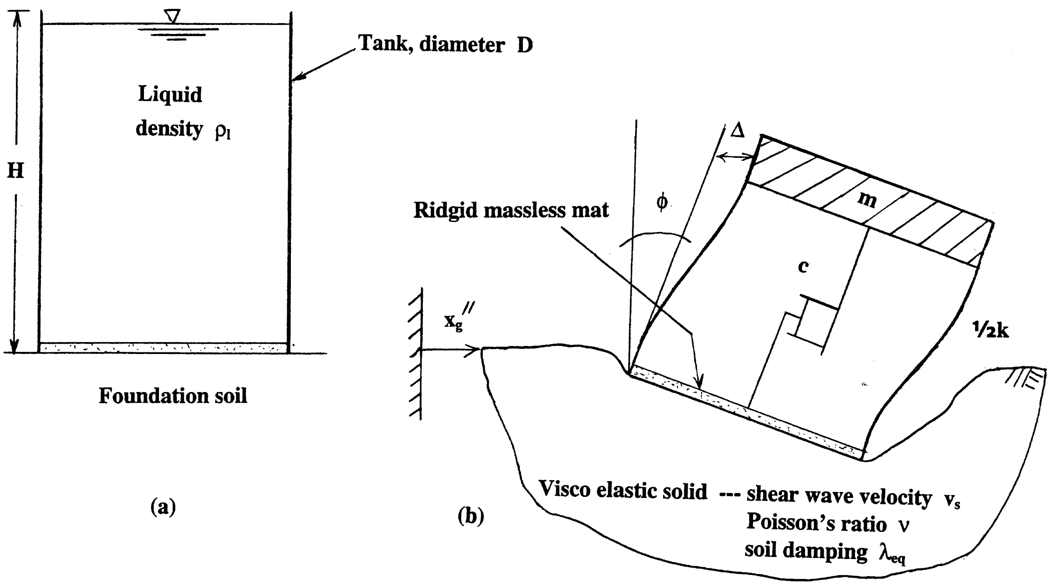


Figure 1 (a) Physical System (b) System analysed under seismic loading

The seismic motion is incident as vertically propagating free field shear waves that result in the free field acceleration $x_g''(t)$ directed along the line of symmetry of the tank. The flexibility of the supporting soil results in the acceleration of the foundation, $x''(t)$, being different from the free field and the foundation motion includes a rocking (rotational) component, $\phi''(t)$.

The response of the tank is considered as being the sum of the impulsive and convective motion described above. In reality the two responses are coupled through the flexibility of the foundation soil. However the validity of the uncoupled assumption has been demonstrated by Veletsos and Tang (1990). In a fixed base condition the tank-liquid system responds as a single degree of freedom system, SDF system, in its fundamental mode of vibration. The appropriate properties of the system have been investigated by Veletsos (1984), Veletsos and Tang (1990) and Malhotra (2001) amongst others. The periods, T_i (impulsive) and T_c (convective), may be calculated from

$$T_i = \frac{2\pi H}{C_i}\sqrt{\frac{\rho_w}{E_w}} \tag{1}$$

$$T_c = C_c \sqrt{R} \tag{2}$$

where H is the height of the liquid, E_w is Young's modulus of the tank wall, ρ_w is the mass density of the tank wall, and C_i is the impulsive period coefficient. C_i is dependent on H/R and t/R, where R is the tank radius and t is the wall thickness. C_c is the convective period coefficient. Values of C_i and C_c are available in Veletsos (1984), NZSEE (1986) and Malhotra (2001). The appropriate values of the participating liquid mass, for foundation loads and moments, for both the impulsive and convective modes are also to be found in these references. The stiffness of the SDF system may be determined from the period and the mass.

The finite flexibility of the half space is introduced using dynamic impedance functions. These are complex functions of frequency and foundation geometry and describe the oscillation of the foundation for a given component of motion. In this application what is required is the impedance function for the rocking component and horizontal translational component of a surface massless circular foundation. A number of authors have presented these functions using a variety of means to determine the values. In this work the data presented by Gazetas (1991) is utilised. The impedance functions are dependent on the properties of the half space which in turn are strain dependent. A strain compatible solution is achieved by using values of the soil properties, i.e. shear modulus and damping, that are consistent with a representative strain calculated from the response of the system.

The integrated system is thus a SDF oscillator supported by a medium that is represented by dynamic impedance functions to account for the translation and rotation of the foundation. A solution in the frequency domain is utilised (Gazetas 1991) and transfer functions formed for points of interest on the system, namely the mass representing the tank/liquid and the foundation. These transfer functions represent the response to an incident harmonic wave of a given frequency. The earthquake motion is expressed in the frequency domain using Fourier transforms and combined with the transfer functions to yield the response of the system. The solution in the time domain is found through inverse Fourier transformation.

3 APPLICATIONS

In this section the method is applied to two common situations. The intention is to investigate the significance of the interaction between the foundation mat and the supporting soil. The two cases are approximately at opposite ends of the spectrum of aspect ratios and tank stiffness. The first entails a concrete tank with a low aspect ratio (height/diameter) founded on competent ground. This tank is considered to be part of a water reticulation system. The second is a tall relatively slender thin walled steel tank founded on soft soil, which is considered to be part of an oil tank farm on low-lying land adjacent to a harbour.

3.1 *A water tank on competent ground*

The analysis concerns a concrete tank of 40m diameter with 10m of contained water. The supporting soil is a saturated clay which has an undrained strength of 120 kPa and a low strain shear wave velocity of 200 m/sec. The tank walls are of a uniform thickness of 200mm and the impulsive period of the tank is 0.144seconds. The earthquake used in the analysis is the Rinaldi record from the Northridge event scaled to have a maximum acceleration of 0.42g.

Figure 2 shows the impulsive acceleration record of the tank accounting for the compliance of the supporting soil. The strain compatible shear wave velocity used in the analysis was 128 m/second and the soil material damping was 25%. This is a large tank with a relatively low aspect ratio. The time history of the acceleration of the tank that results when the tank is sited on rigid rock is shown in Figure 3. Considerable difference is seen to exist between the two responses. Including the compliance of the soil has produced a lower frequency response and significantly lowered the accelerations by a factor of almost two. The response spectra of the two motions are shown in Figure 4.

The convective response of the tank may also be modelled as a single degree of freedom system. The convective period of this tank is 7.78 seconds, with structural damping taken as 0.5%. The contribution from the convective mode is often thought to be smaller than the impulsive in most cases. To investigate this the convective response of the tank was computed including foundation compliance and is shown in Figure 5. The accelerations are lower than those of the impulsive mode and the long period nature of the oscillations is evident. Inclusion of foundation compliance was found to be insignificant in this mode for this tank.

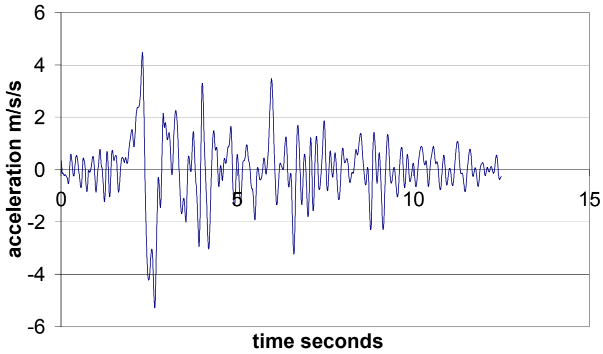


Figure 2 Impulsive acceleration of tank with foundation compliance included

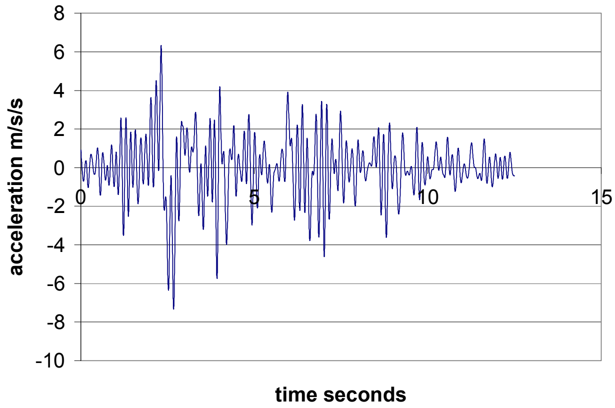


Figure 3 Impulsive acceleration of tank on a rigid half space

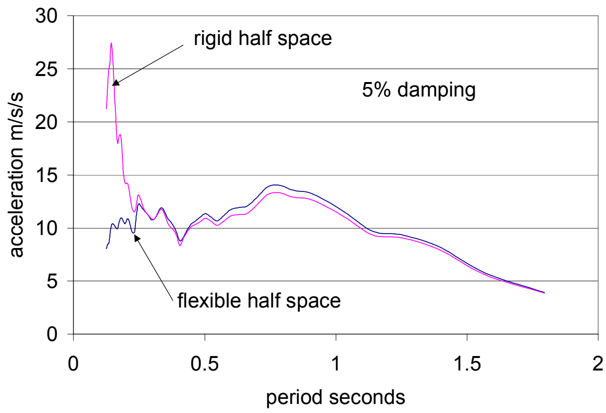


Figure 4 Impulsive acceleration response spectra for tank on two ground conditions

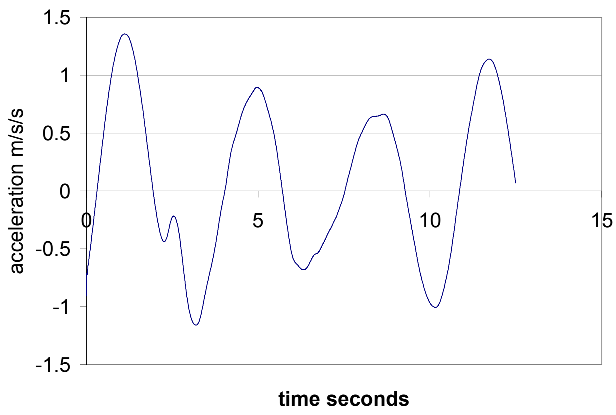


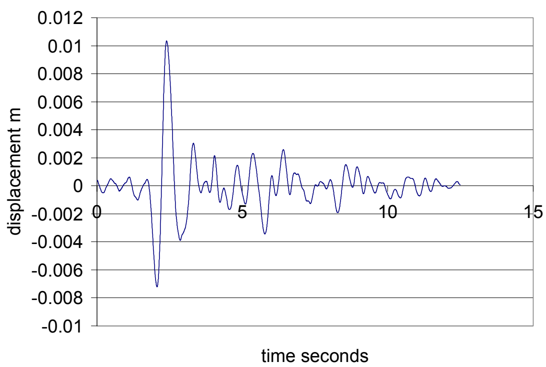
Figure 5 Convective acceleration response of tank

3.2 *An oil tank on soft ground*

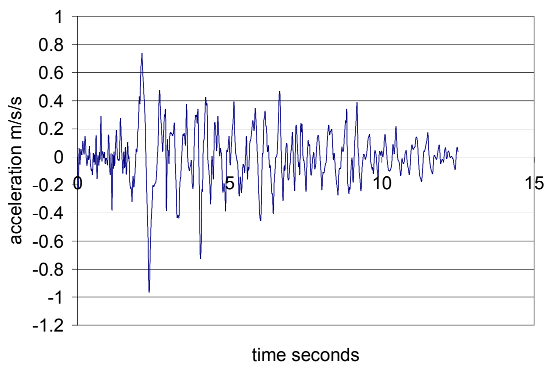
The second example concerns a steel oil tank of height 15m, a diameter of 10m and a wall thickness of 10mm. Conceptually the tank is one of a number situated closely adjacent to a harbour or river mouth. This is a common situation in many parts of the world, including New Zealand. The foundation conditions are a soft clayey silt with a shear wave velocity of 120 m/sec and an undrained strength of 80 kPa. The fixed base impulsive period of the tank is 0.167 seconds and the convective period is 3.31 seconds. The earthquake used in the analysis is the same as in the first example.

Considering the impulsive mode of response, the significance of soil – structure interaction may be seen in the following four figures. Figure 6 shows the horizontal displacement and acceleration of the foundation mat relative to the free field. The flexibility of the foundation soil has resulted in a maximum relative displacement of the mat to the surrounding soil of 0.01m and a maximum relative acceleration of 1m/s/s.

The influence of rotational displacement of the mat foundation is shown in Figure 7. Rotation of the foundation has led to a maximum horizontal displacement of the tank of 0.03m. The maximum acceleration of the tank as a direct result of rotation is 3.0 m/s/s. These figures are considerably greater than those in the first example where the tank had a lower aspect ratio and the soil was more competent. The soft soil and tall tank at this site has resulted in significant interaction that has lowered the accelerations and the predominant frequencies. Substantial reduction in design forces will result. Figure 8 shows the resulting acceleration of the tank.

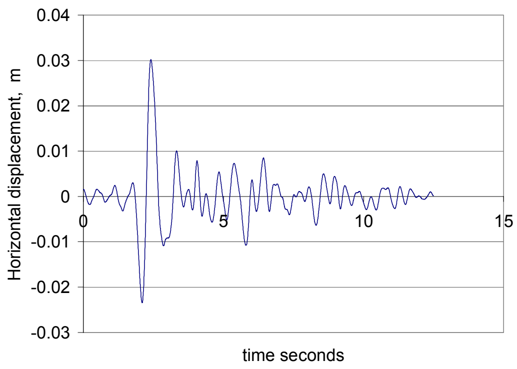


(a) Displacement

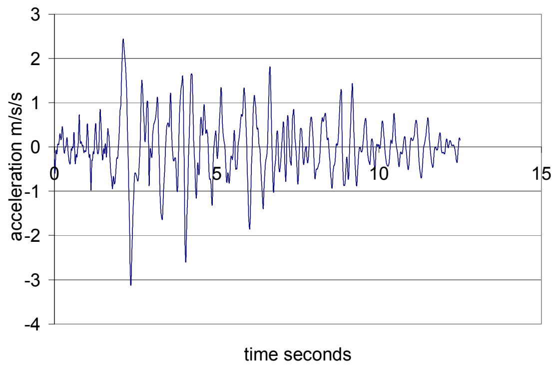


(b) Acceleration

Figure 6 Response of mat foundation relative to free field



(a) Displacement, m



(b) Acceleration, m/s/s

Figure 7 Response of tank from rotation of foundation mat

The substantial effect of soil/structure interaction for this example is shown by the response spectra in Figure 9. Response spectra are shown for the fixed base (rigid half-space) and the more realistic flexible soil condition. Compliance of the foundation soil has hugely reduced the high response in the high frequency range but has increased substantially the response in the midrange of frequencies.

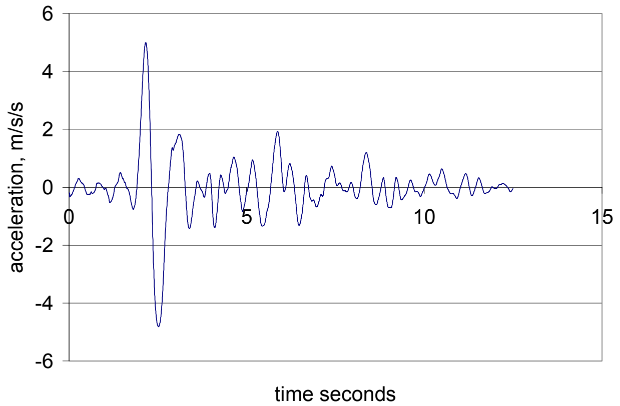


Figure 8 Impulsive acceleration of tank including foundation compliance

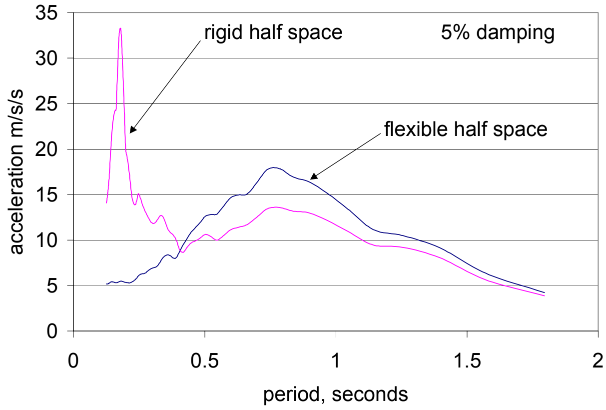


Figure 9 Impulsive acceleration response spectra of tank for two foundation conditions

3.2.1 *Bearing capacity and horizontal shear of mat foundation*

The surface mounted foundation of the tank is subject to overturning moment and horizontal shear. In traditional terms the situation is one of inclined and eccentric undrained loading of the mat foundation. For this situation the bearing capacity equation may be written as

$$q = ci_c N_c \tag{3}$$

where q is the ultimate bearing stress, i_c is the inclination factor, N_c the bearing capacity factor (5.14) and c is the cohesion (undrained shear strength). As an approximation the foundation has been considered square with a width determined such that the area equals that of the 10m diameter circular foundation. This results in a square foundation of width 8.86 metres. The value of i_c used is that suggested in Eurocode 8 (1997). The method of Meyerhof (1963) to account for eccentric loading is implemented. This method reduces the bearing area such that the centroid of the bearing area lies vertically below the line of action of the eccentric load.

The factor of safety in bearing, calculated as a function of time, is shown in Figure 10. The static factor of safety is seen to be 2.8. There are two excursions into the region where the factor of safety is significantly less than 1, implying failure in bearing. Failure of the foundation may occur, although it must be remembered that the factor of safety reduces to less than 1 only momentarily. Significant deformations will take place.

The factor of safety with respect to horizontal shear may be computed in a similar manner. The <u>inverse</u> of the factor of safety in shear for the mat is shown in Figure 11. The static value of the undrained strength has been assumed applicable under dynamic conditions in both this analysis

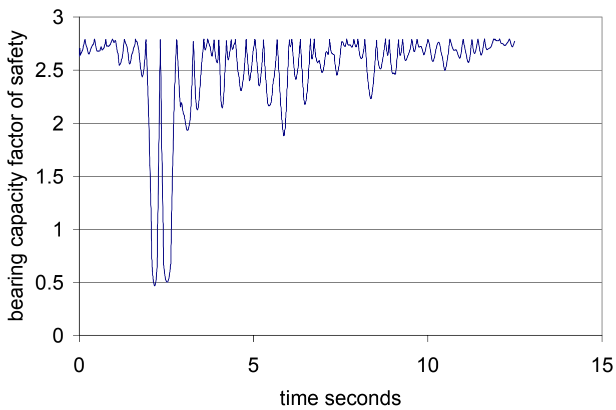


Figure 10 Bearing capacity factor of safety as a function time

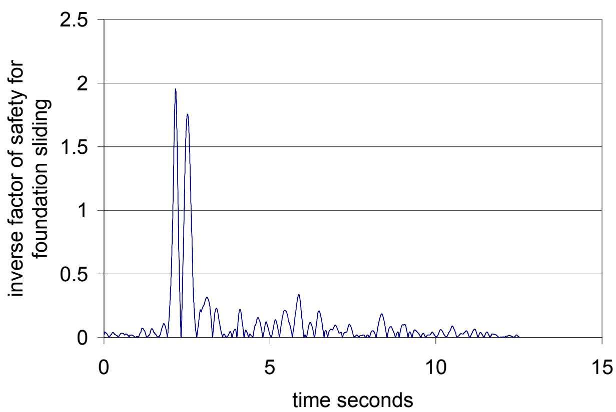


Figure 11 Inverse of the factor of safety for horizontal shear of foundation

and that concerning bearing capacity. This is probably conservative since most cohesive soils show strength gain under dynamic conditions. Again two excursions into the domain implying failure occur. Clearly the foundation is unsatisfactory in both bearing and shear.

4 CONCLUSIONS

The seismic response of two very different tanks founded on different foundation conditions has been presented. The results show significant compliance effects in the impulsive mode for both tanks. In particular the thin walled tall oil tank on soft ground displays very significant foundation compliance effects. The rocking of the oil tank on the mat foundation results in a large reduction in seismic forces and moments but with increased displacements. Lower frequency motion and reduced accelerations result due to foundation rocking and translation with associated soil and radiation damping. The response of the oil tank in the mid-frequency range is increased due to the compliance effects.

The squatter water tank on competent ground also shows significant soil / structure interaction effects in the impulsive mode. This foundation is a stiff cohesive soil which would not be regarded as being problematic from a geotechnical engineering point of view. These results suggest that even on reasonable ground there is likely to be soil / structure interaction effects that are worth considering in design. Little effect of foundation compliance was found in the convective response.

The results of computing a time dependent bearing capacity and horizontal shear factor of safety have been presented. This is a useful method of identifying the capacity of the foundation soil to sustain the moment and horizontal shear loading associated with seismic loading.

The intention of this work has been to find an effective avenue for the design of tanks subjected to seismic loading accounting for the foundation conditions. The technique described here falls intermediate between short hand calculations and elaborate finite element studies or the like. To this end it is considered to be a useful design tool.

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