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Constitutive Models for Rubber

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Different numerical models for the hysteretic behaviour of HDRB's on the dynamic response of base-isolated structures with lumped-mass models under seismic loading

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ABSTRACT: The effect of seismic base isolation by HDRB's (**High Damping Rubber Bearings**) is based on two main effects. The one is the capability of large elastic deformations which increases the fundamental period of the structure and reduces the seismic response. The second effect is the non-elastic absorption of the energy introduced by the earthquake by means of the hysteretic damping.

An adequate description of the nonlinear characteristic of the HDRB's and a correct modelling of the overall structure are presuppositions for a realistic estimation of the mechanism and effectivity of such a base isolation.

Three different numerical approaches for the description of HDRB's have been developed, in order to show the influence on the results. The effect of these approaches on the dynamic response are studied with lumped-mass models representing a base-isolated storage tank for liquefied natural gas (LNG). The maximum accelerations of the isolated structure are compared, in order to verify the accuracy of the numerical approaches and the boundaries of their applicability.

1 INTRODUCTION

For above-ground LNG-storage-tanks the state of the art is defined by the Full Containment Type (Figure. 1). The liquid is stored by a steel inner tank. A prestressed concrete outer tank protects the sensitive inner tank against external hazards and serves as back-up-pool in case of failure of the inner tank.

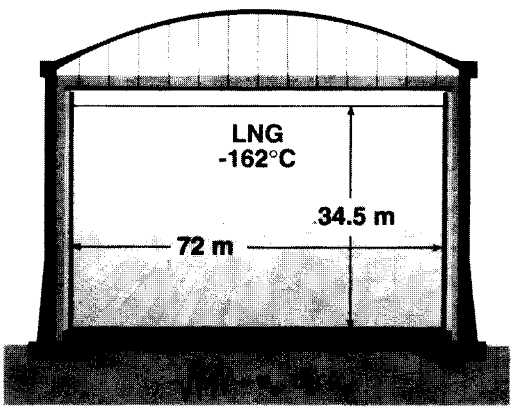


Figure. 1: LNG-storage-tank: Full Containment Type (V = 140,000 m³)

The steps which are required for the earthquake design of such a tank system are typical also for other structures. First we need an idea of the failure modes and the corresponding design criteria. For a containment acc. to Figure. 1, one important criterion is uplifting of the inner steel tank and consecutive buckling or elephant-footing of the tank wall due to the horizontal excitation (Figure. 2). The most important problem in this respect is whether a base isolation is required in order to reduce this risk of elephant-footing or not. For answering this question, the idealization by a so-called tuning fork-model is suited best. The overturning moments of the inner tank, which may cause uplifting and buckling, have to be sustained by a rotational spring, which may represent also the nonlinear uplifting characteristic of the inner tank. With this model, the effect of a base isolation on the uplifting of the inner tank can be analyzed in a reliable way.

For other design criteria, e.g. buckling of the cupola of the outer tank under vertical accelerations, other idealizations are required. Thus, the computational model has to be chosen always with regard to the individual design question.

The tuning fork model of figure. 2 can be simplified further by an oscillator with three degrees of freedom (Figure. 3). The relevant influences –

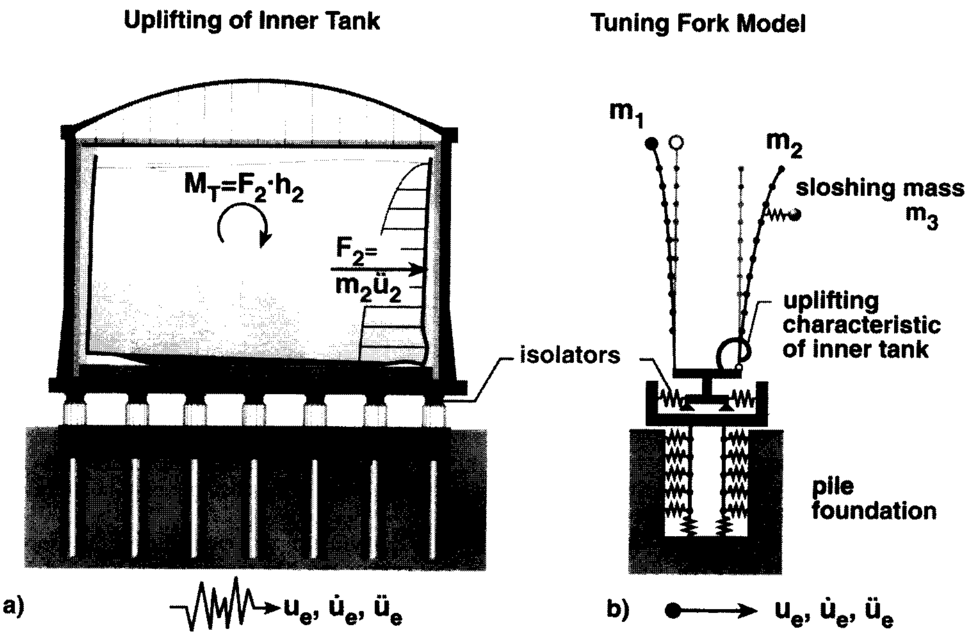


Figure. 2: Modelling of base-isolated tank as tuning fork model including uplifting effects of inner tank

characteristic of base isolation, mass of outer tank, stiffness of inner tank, impulsive and sloshing mass of liquid – can be depicted also by this model without loss of accuracy. The absolute displacement of the subsoil and the masses m_1, m_2, m_3 are denoted by u_e, u_1, u_2, u_3. The elongation of the springs K_1, K_2, K_3 are given by $u_e - u_1$, $u_1 - u_2$, $u_2 - u_3$.

It is a crucial question, in how far the reliability and accuracy of an analysis can be improved by a more discrete idealization (Figure. 4). For the practical design it seems more efficient in most cases to apply simple models which are related to the individual design task rather than increasing the number of elements.

In the following we consider the effect of different modelling of isolators on the 3DOF-oscillator with the numeric characteristics shown in Figure. 3 (corresponding to an LNG-tank with V = 140,000 m³). The periods of the three eigenmodes are determined by

- the base isolation,
- the inner steel tank and
- the sloshing of the liquid.

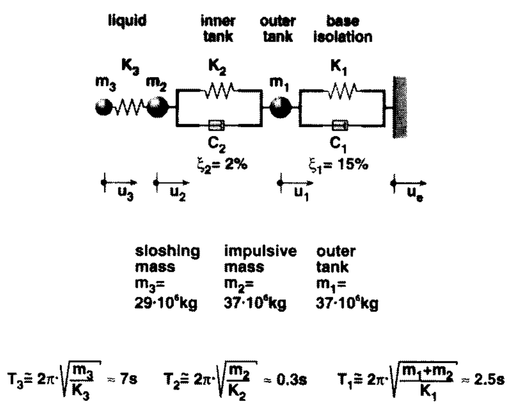


Figure. 3: 3DOF-oscillator and numeric characteristic for an LNG-tank with V = 140,000 m³

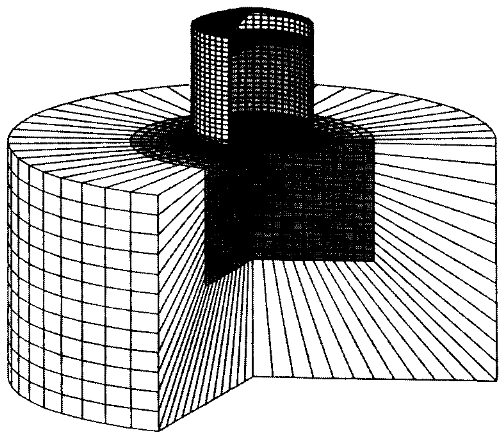


Figure. 4: Discrete idealization of containment, liquid and subsoil

The basic stiffness K_1 of the isolators has been designed in order to increase the period T_1 to 2.5 s. This can be reached by the arrangement of about 460 isolators as described below.

For the intended reduction of the seismic response, a high damping ratio of the isolators is decisive. The computational modelling of the structure and of the damping is the main subject of this report. The consideration of the different types of energy which occur during an earthquake allows a better understanding of the basic actions.

2 COMPUTATIONAL MODELLING OF ISOLATORS

We consider High Damping Rubber Bearings, briefly HDRB´s, which are suited well as isolators. Figure. 5 shows a typical characteristic, which has been found by tests. For the computational description of such a characteristic, we have studied three different models.

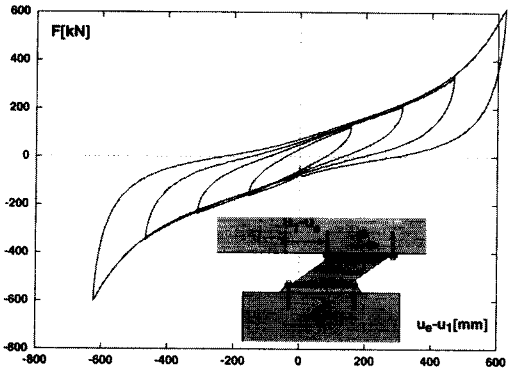


Figure. 5: Typical characteristic of a High Damping Rubber Bearing (HDRB)

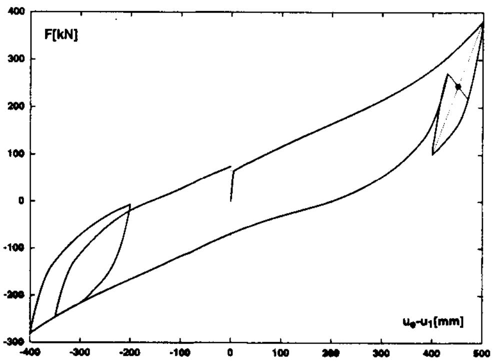


Figure. 6: Model 1: Direct numerical description

Model 1 applies a direct numerical description (Figure. 6). The envelope of the hysteresis is described by about 50 points. For a partly unloading and reloading, special procedures have been developed for shifting and reflecting the relevant parts of the envelope.

In the second model, two nonlinear springs are superimposed (Figure. 7). The elasto-plastic spring (1a) is intended to cover the hysteresis, the multilinear elastic spring (1b) simulates the stiffening of the isolators at higher loads. In this second model only seven parameters are required, which is less expensive than the detailed numerical description of model 1.

In most cases the model 3 is applied (Figure. 8). It combines an elastic spring (K_1) with a viscous damper. First a damping ratio ξ_1 is derived from the hysteresis in a semi-empiric way by comparison of the elastic energy $E_{elastic}$ and the area of the hysteresis loop. In a second step the coefficient C_1 for a velo-

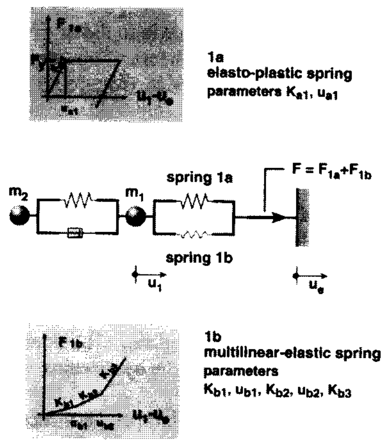


Figure. 7: Model 2: Superposition of two nonlinear springs

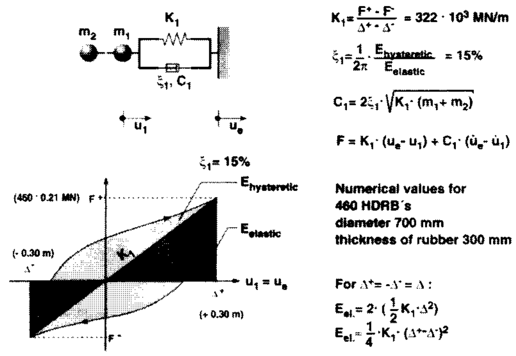


Figure. 8: Model 3: Elastic spring and velocity-dependent damper

city-dependent damping force is defined by $C_1 = 2\xi_1 \cdot [K_1 \cdot (m_1 + m_2)]^{0.5}$, the inner steel tank being considered rigid compared to the isolators for this assessment.

The overall force F which is transferred from the subsoil into the structure is given by

$$F = K_1 \cdot (u_e - u_1) + C_1 \cdot (\dot{u}_e - \dot{u}_1) \quad (1)$$

At least for a load-history, which is not symmetric to the origin, there is no clear theoretical foundation for this procedure. Nevertheless it is practicable and delivers reasonable results, as we will see later.

In our parameter studies we assumed a base isolation consisting of 460 HDRB's with the characteristic shown in Figure. 5. For the application of model 3 acc. to Figure. 8 we had first to estimate the maximum deformations of the bearings (± 0.30 m) and the corresponding force F (460 · 0.21 MN). From this we got the stiffness K_1 = 322 MN/m and by evaluation of the hysteretic area the damping ratio ξ_1 = 15%.

How do these three models fit to reality, that means to the test results of the bearings?

For a load history which is symmetric to the origin the direct description of model 1 delivers of course a good agreement with the test result (Figure. 9). However, the real load history of isolators during an earthquake is not symmetric to the origin at all. Figure. 10 shows the loading und unloading paths obtained as result of a time history analysis with HDRB's acc. to model 1. The paths seem quite reasonable but we have to realize that they cannot be verified by test results as such results are not available acc. to our knowledge.

Figure. 11 shows the comparison for model 2. It can be seen that the elasto-plastic spring (1b) does not cover adequately the increase of the hysteresis for higher loads.

For model 3 (elastic spring plus damper), a direct comparison of the computational model with the test results is not possible. For the assessment of the quality of model 2 and 3, we consider the results of parameter studies on the 3DOF-oscillator of Figure. 3. The standard for the quality of these models are the results obtained with model 1, which are postulated to be correct, because model 1 describes the test results of the bearings most exactly.

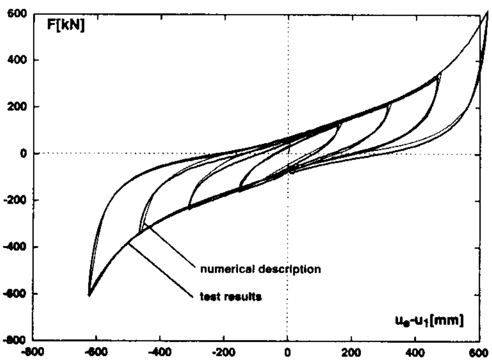


Figure. 9: Comparison of test results and numerical description of HDRB's by model 1

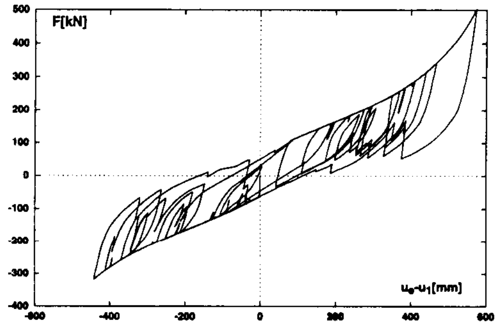


Figure 10: Loading and unloading paths of isolators during an earthquake as result of a time history analysis

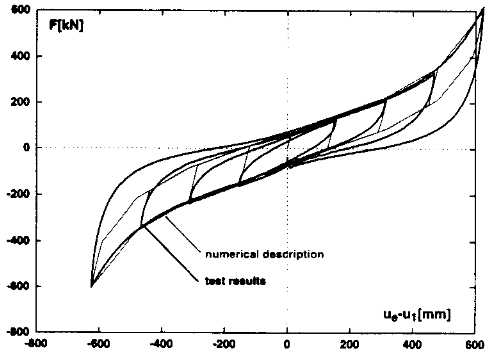
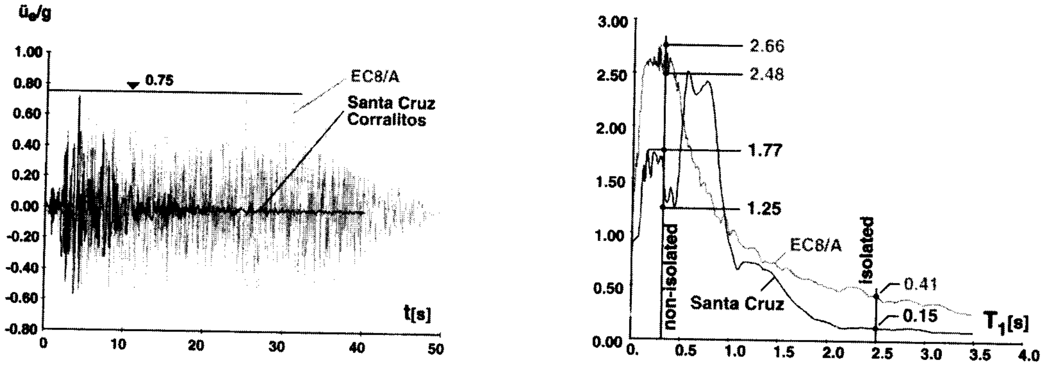


Figure. 11: Comparison of test results and numerical description of HDRB's by model 2

3 RESULTS OF TIME HISTORY ANALYSES (PGA = 0.75 G)

Our parameter studies are based on an artificial time history fitting the response spectrum given in Eurocode 8 for soil type B (Figure. 12). The response value for a non-isolated tank is given by the period of the inner steel tank of 0.3 s to about 2.5 and for an isolated structure with a period of 2.5 s to about 0.4, both for a damping ratio of 5%. In reality the steel inner tank has a lower damping ratio and therefore a higher response, whilst for the isolated system we aim at damping ratios much higher than 5%.

Additionally we consider the natural acceleration time history of Santa Cruz / Corralitos earthquake. For the period of 2.5 s, which corresponds to an iso-



acceleration time histories (PGA = 0.75g)

response spectra for $\xi_1 = 5\%$

Figure. 12: Acceleration time histories and response spectra for typical earthquakes

lated system, the response is only 0.15 for this earthquake. Both time histories have been scaled to a PGA of 0.75 g for this parameter study.

Figure. 13 show the displacement history of the isolators for the first 20 s of the earthquake as result of the time history analysis of the 3DOF-oscillator acc. to figure. 5. The plotted values $u_e - u_1$ describe the shear deformation of the isolators.

The results are quite similar for the three models. We recognize clearly the period $T_1 = 2.5$ s, which was intended in the design of the base isolation. The results of model 1 are postulated to be the correct scale. There is practically no difference of model 1 and model 3, the maximum being 0.30 m, which had been assumed for the evaluation of stiffness and damping ratio of model 3. Contrarily the model 2 yields in general smaller deformations.

With regard to overturning of the inner tank as main design criterion, the acceleration $\ddot{u}_2$ of the inner tank and the liquid mass m_2 is the most important result. It is shown in Figure. 14 for model 1 and model 3. We recognize again the period of 2.5 s given by the isolators. The maximum acceleration is 1.3 m/s² for model 1 and 1.6 m/s² for model 3 with a damping ratio of 15%.

The higher acceleration of model 3 is due to an undesired transfer of forces from the subsoil into the structure by the damper. This can be seen also from the more pronounced peaks, which occur with the period of the inner tank. After the end of excitation, that is after 50 s, the oscillation comes to an end much earlier for model 3 than for model 1. The reason is that in model 3 the damping ratio of 15%, which has been defined for the maximum displacement, is kept constant also for small displacements. In reality the damping of the bearings is less for small displacements. This effect is included only in model 1 and 2.

From a scientific point of view, the model 3 has some shortcomings compared with the postulated

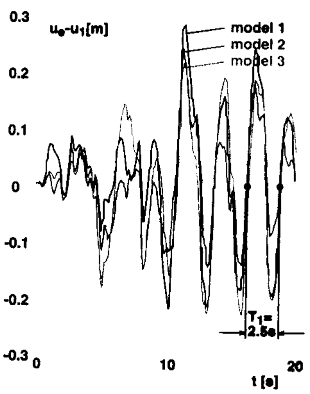


Figure. 13: Displacement history of isolators for an artificial acceleration time history (EC 8 / soil type A / PGA = 0.75 g)

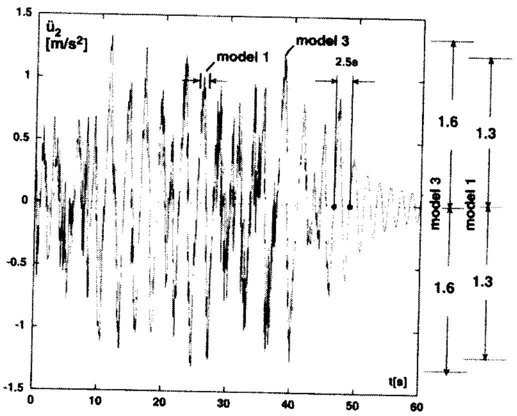


Figure. 14: Acceleration history of inner tank for model 1 and 3

reality of model 1. However, the deviation of the acceleration of the inner tank – 1.6 m/s² instead of 1.3 m/s² – remains within the accuracy, which can be reached within such a dynamic analysis. Therefore the model 3 is also acceptable for the practical design.

4 DISCUSSION OF RESULTS WITH REGARD TO LNG-STORAGE-TANKS

In Figure. 15 we see the most important dynamic responses of the tank system acc. to figures. 1 and 2, that is the maximum acceleration $\ddot{u}_2$ of the inner tank related to the PGA, in dependence of the damping ratio ξ_1 for model 3. The influence of ξ_1 is much more pronounced for the artificial time history acc. to EC 8 than for the natural time history of the Santa Cruz earthquake.

In Figure. 16, the dynamic response for a time history acc. to EC 8 / A is shown in dependence of the modelling of isolators. For a PGA of 0.75 g, model 3 yields a higher response than model 1 (1.6 m/s² instead of 1.3 m/s²). However, for a PGA of 0.4 g, the opposite tendency was found. Nevertheless, this figureure confirms the earlier statement that the three models of isolators are equivalent for the use in the practical design. Although the model 3 has some shortcomings from a theoretical point of view, it allows the most simple description of the HDRB´s in the dynamic analysis.

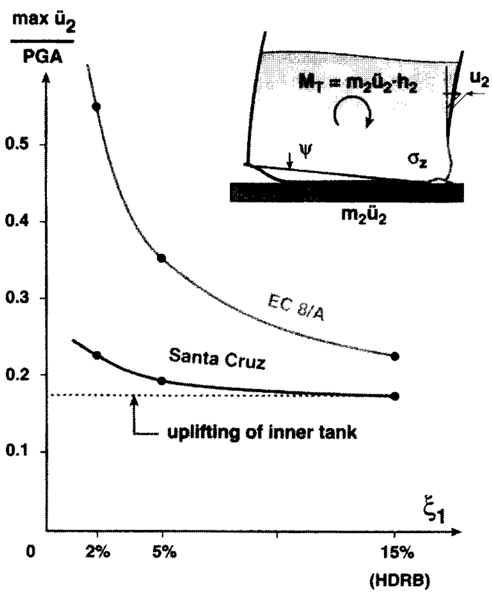


Figure. 15: Accelerations and overturning moments of inner tank depending on the damping ratio $\xi 1$ (for model 3)

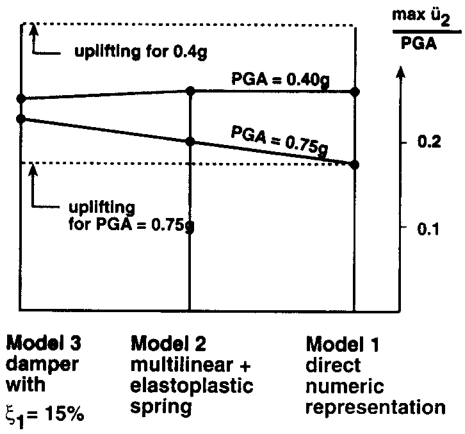


Figure. 16: Accelerations and overturning moments of inner tank depending on modelling of isolators (for $\xi 1$ = 15%, time history acc. to EC 8 / A)

The meaning of these results for the design of the inner tank can be seen from the dotted horizontal lines in Figure. 15 and Figure. 16. They mark the level, where uplifting and elephant footing occur. This is the case for an acceleration $\ddot{u}_2$ = 1.35 m/s².

That means that the inner tank cannot withstand the higher PGA of 0.75 g with a sufficient safety margin, at least, if the artificial time history acc. to EC 8

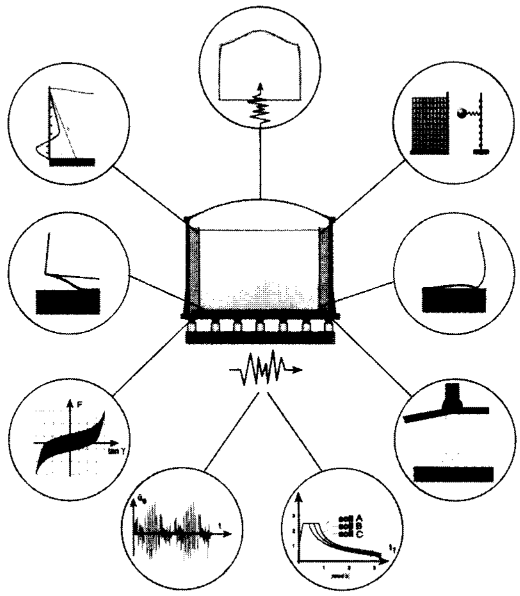


Figure. 17: Features to be delt with in the seismic design of an LNG storage tank

is assumed. In this case the base isolation should be improved by increasing the thickness of rubber.

However, an earthquake with PGA = 0.4 g could be sustained well with the base isolation assumed within this case study.

5 CONCLUSIONS

There are several possibilities for the numerical description of the damping characteristics of the seismic base isolation. The most simple model is an elastic spring combined with a velocity-dependent damper. Despite its theoretical shortcomings it is sufficient with regard to the accuracy which can be reached in any numerical analysis.

Figure. 17 shall address the complexity of the earthquake analysis of an LNG-storage tank. The appropriate modelling of the hysteresis of the isolators is only one of many tasks. Equally important are
- the modelling of the total system of the structure with regard to the individual design question
- the definition of the seismic input from the subsoil into the structure and
- the detailed design of the critical parts of the structure, for example the bottom corner of the inner tank.

These items cannot be treated separately. A reliable design requires the consistent consideration of all these features.

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