

SEISMIC RISK ASSESSMENT OF LNG STORAGE TANKS

William E. Gates (I)

David P. Hu (II)

Presenting Author: W.E. Gates

SUMMARY

This paper presents a comprehensive approach for the seismic review of existing LNG storage tanks and supporting facilities. The approach considers the seismic hazards from ground motion, surface fault rupture, and soil instability such as liquefaction. Both deterministic and probabilistic methods are used in the assessment of these hazards. Dynamic properties of the soils and the soil-structure-fluid system are measured by field tests and correlated with analytical models. Dynamic soil-structure interaction analyses are performed using finite element methods to assess the reserve capacity of the existing storage tanks. Examples from an actual case study are included to illustrate the approach and methodology.

INTRODUCTION

Earthquake safety design and review of LNG storage facilities has undergone significant change over the past 15 to 20 years since the beginning of such construction in California. Present regulations for the siting of LNG facilities in high seismic areas have been upgraded to closely parallel the criteria used for siting and design of nuclear power plants.

This paper deals with the problems associated with evaluating the earthquake safety of an existing LNG storage tank facility constructed to the less stringent seismic regulations of the mid to late 1960s and early '70s. In the early 1960s, the seismic force design of an LNG storage tank was based on a single lateral force coefficient applied to the tank as a rigid body in a manner similar to that used in the design of one- and two-story structures or vessels in a refinery. By the mid to late 1960s, it was recognized that fluid motions in a tank could contribute significantly to its response and the lateral force coefficient was applied only to the rigid impulsive component of the tank fluid and not to the convective or sloshing component. The influence of soil-tank interaction and tank flexibility were not recognized as a design consideration until the 1970s.

(I) Consultant, Dames & Moore, Los Angeles, California.

(II) Civil Structural Engineering Supervisor, San Diego Gas and Electric, San Diego, California.

LNG STORAGE TANK

Figure 1 depicts the typical above-ground LNG storage tank. The vessel consists of two concentric cylindrical flat-bottomed tank shells with the angular space between filled with a perlite insulating material. The inner tank is constrained against uplift by a set of hold-down bolts or straps along the perimeter. These straps are anchored into a concrete mat that forms a pile cap and is supported on a closely-spaced gridwork of vertical reinforced concrete step-tapered piles.

EARTHQUAKE FAILURE MODES

For the typical above-ground LNG tank placed on a pile-supported mat of reinforced concrete, the following are some of the potential modes of earthquake distress or failure that must be reviewed:

- o Pile foundation failure in shear or end bearing in the soil;
- o Pile failure in shear, bending, tension or compression;
- o Mat failure in punching shear at the outer piles, or bending;
- o Tank buckling causing pipe or weld rupture;
- o Tank uplift with accompanying yield of hold-down straps;
- o Tank sliding (e.g., inner tank relative to outer on perlite insulation blocks) causing rupture of shell or interlocking piping; and
- o Shell rupture at welded seams due to tension stresses beyond ultimate strength of the steel.

GEOSEISMIC HAZARDS

When siting a new LNG facility or reviewing an existing LNG facility, the following geoseismic hazards are of prime concern: strong ground shaking; soil failure due to liquefaction; surface fault displacement; flooding; and fire. Strong ground shaking is the major consideration in earthquake design and review. Soil failure due to liquefaction is a consideration if the site has a high water table, soft, loosely placed sandy soils, and an anticipated strong ground motion potential. As such soils liquefy, losing their lateral and vertical strength, pile and spread foundation systems tend to settle into the soils, causing large permanent displacements of the structure. Surface fault displacement caused by the abrupt rupture of a fault system directly below the LNG tank may cause large differential displacements. Flooding from seismic seawave, seiche, or the failure of an upstream dam may be a consideration in low-lying floodplain sites. Fire is a secondary form of hazard, caused generally by the rupture of a gas line or the spillage of LNG from ruptured tanks.

SEISMIC DESIGN CRITERIA

The Public Utilities Commission (PUC) has recently adopted a series of safety regulations (General Order No. 112-D) (Ref. 1) for the siting

and operating of LNG facilities in California. A significant portion of the regulation deals with the seismic safety features and related design considerations. These regulations require a complete geoseismic hazards survey of the site prior to issuing a construction permit. Furthermore, they require design of the LNG facility to meet both an Operating Basis Earthquake (OBE) and a Safe Shutdown Earthquake (SSE). These two earthquake events are defined in terms of average recurrence interval as 500 years for the OBE and 10,000 years for the SSE. Following guidelines similar to those of the Nuclear Regulatory Commission, the tanks must remain functional through the OBE and capable of containing the LNG without spillage through the SSE.

LNG STORAGE TANK REVIEW PROGRAM

The following is an outline of the overall program for comprehensive review of existing LNG storage tanks:

1. Assessment of geoseismic hazards;
2. Assessment of existing tank construction through field survey and testing;
3. Analysis of the seismic capacity using simplified and complex modeling procedures; and
4. Comparison of the earthquake demand with the measured strengths of the tank and its foundation system.

These basic elements of the review program are accomplished in the following sequence.

Field Survey and Test Program

The field survey and testing program are conducted before the geoseismic hazards investigation in order to provide data for evaluation of the liquefaction potential and the strong ground motion criteria.

The field program consisted of:

- o Geological survey to assess surface fault displacement hazards;
- o Geophysical survey around the tanks to assess subsurface features and dynamic soil properties;
- o Soil exploration, drilling and sampling program to provide supplemental data on the dynamic and static properties of the soils around the pile foundations;
- o Inspection of the tank and its foundation to verify as-built conditions and state of repair; and
- o Vibration monitoring under low-level ambient and forced vibration (drop weight) to assess the dynamic vibration characteristics of the tank, liquid LNG, soil-pile system and site.

Geoseismic Hazards Assessment

The strong ground motion hazard was evaluated using two methodologies: a probabilistic representation of past earthquake

activity was mathematically modeled and evaluated at the site for events having a recurrence interval of 500 years and 10,000 years (e.g., OBE and SSE, respectively). Peak ground accelerations determined by this procedure were compared with a deterministic estimate of ground motion at the site considering the maximum potential earthquake on each of the seismogenic sources (e.g., active faults). Site-specific response spectra for a deep alluvial profile were determined. For soil structure interaction analysis purposes, time history motions from historic events recorded on similar soils in the same seismogenic region (e.g., El Centro, 1940) were synthesized to match the site-specific response spectra.

Liquefaction potential at the site was evaluated using the simplified procedure developed by Seed (Ref. 2). In this procedure, the shear stresses required to cause liquefaction in saturated soils are evaluated based on blowcount data obtained from borings at the site. Approximate values of induced shear stresses in the soil with depth for given levels of earthquake acceleration are compared to induced shear stresses required to cause liquefaction.

SEISMIC ANALYSIS OF LNG STORAGE TANK

Two separate methods for mathematically modeling the behavior of fluid storage tanks supported on flexible foundations are currently in use. These are shown schematically in Figures 2 and 3. The first is a simple stick model in which the equivalent impulsive and convective components of liquid motion are represented by two independent spring-mass systems attached to a rigid mat without direct connection to the shell of the tank. The double tank shell is independently represented by a cantilever beam that is rigidly attached to the foundation mat. Lateral, vertical and rocking stiffness of the soil-pile system is represented by equivalent concentrated springs. This simplistic model of the soil-pile-tank-liquid interaction problem is currently used for seismic design of fluid storage tanks. Such a model at best can only approximate the tank seismic behavior and its interaction with the soil.

When reviewing an existing tank where information on the material properties of the structure and surrounding soil environment are well-defined, a more refined form of analysis may be employed using an axisymmetric finite element model to gain the optimum information. Figure 3 depicts such a model. In this model, the tank shell is represented by a series of conical shell elements; the annular space between the two concentric shells is represented by a series of solid ring elements representing the perlite insulation; the liquid LNG is represented by solid ring elements with characteristics approaching those of a liquid; the reinforced concrete mat is represented by shell elements; the piles are represented by rings of pile elements possessing the characteristics of individual piles; and the soil is represented by solid ring elements with material characteristics compatible with the large strains associated with earthquake.

Earthquake motions at the surface are fed into a one-dimensional soil profile model of the free field and deconvolved to the base level of the axisymmetric finite element model, as shown in Figure 3. These motions are then applied to the base of the axisymmetric model. The tank and its pile supported foundation interact with the surrounding soil field to reproduce the effects of soil-structure interaction.

For the case study, the simple stick model was used in preliminary investigations to identify the need for the more refined model. The axisymmetric finite element model was used as the tool for detailed review of the tanks and their foundation systems.

EARTHQUAKE RISK ASSESSMENT

Results of the axisymmetric finite element analysis included: tank displacement response; shell stresses; foundation mat forces; pile forces; and acceleration response.

Figure 4 depicts the deformation patterns in the finite element model at the time of maximum tank response. Figure 5 represents maximum shell displacements and stresses at the time of maximum response.

CONCLUSIONS

Seismic design and review criteria for LNG storage tanks has undergone significant change over the past decade and a half. Static lateral force procedures for earthquake analysis of these tanks is no longer considered acceptable in high seismic areas of the world. This is particularly so for tanks supported on piles or elevated above the ground surface. In these situations, soil-structure interaction plays a significant role in the dynamic forces imparted to the tank during earthquake.

When reviewing existing LNG facilities, in which soil-structure interaction is a potential, analytical procedures and test programs should be developed that accurately assess the characteristics of the tank under dynamic conditions associated with large earthquake strains. Rational criteria based on a detailed geoseismic hazard assessment should be prepared to provide meaningful data for the analysis.

REFERENCES

1. General Order No. 112-D, "Rules Governing Design, Construction, Testing, Maintenance and Operation of Utility Gas Gathering, Transmission and Distribution Piping Systems," issued by the Public Utilities Commission of the State of California, July 5, 1979.
2. Seed, H.B., "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes," Journal of the Geotechnical Engineering Division, ASCE, vol. 105, No. GT-2, February 1979, pp. 201-255.

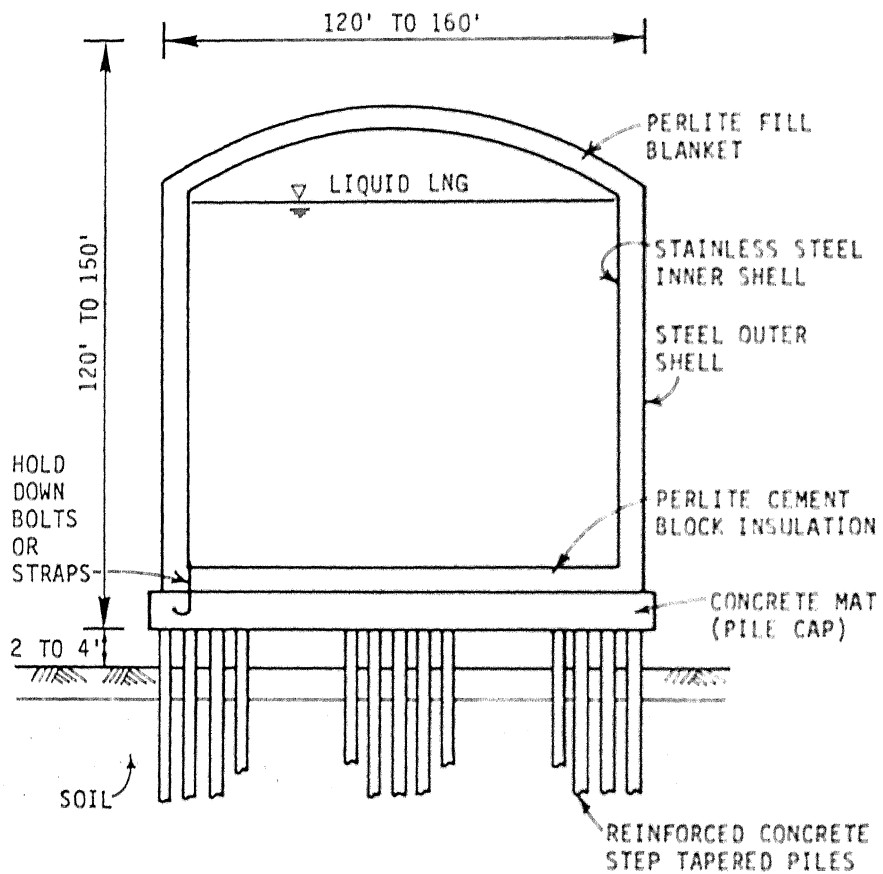


FIGURE 1. LNG STORAGE TANK

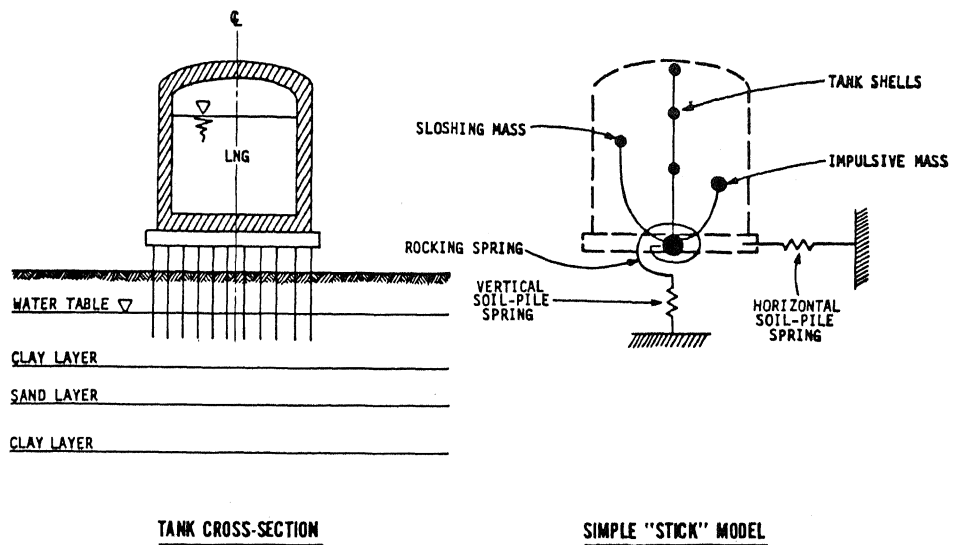


FIGURE 2. SIMPLE TANK MODEL

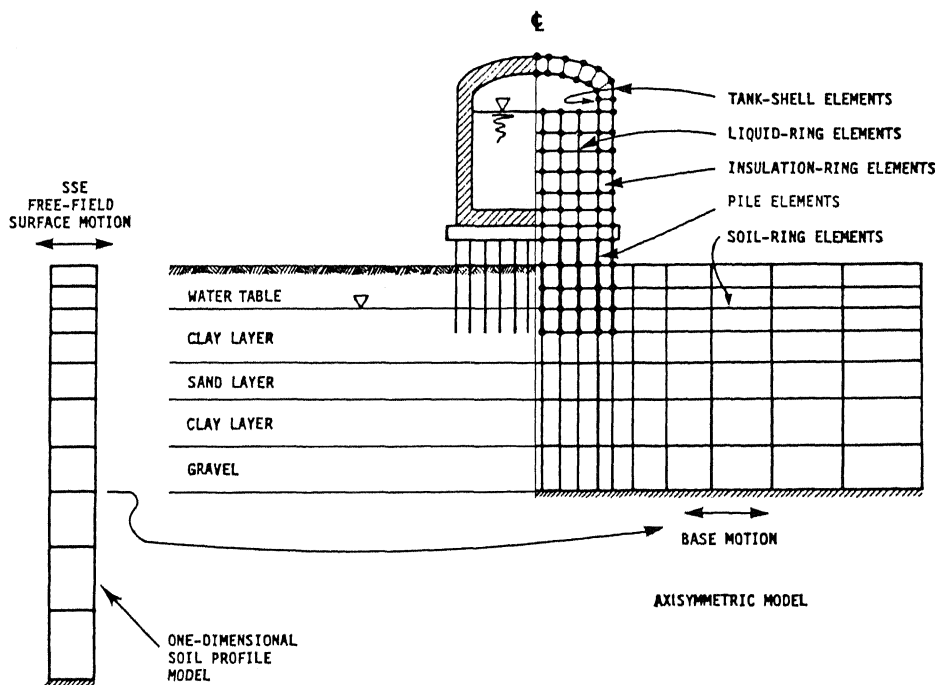


FIGURE 3. SOIL-STRUCTURE INTERACTION MODEL

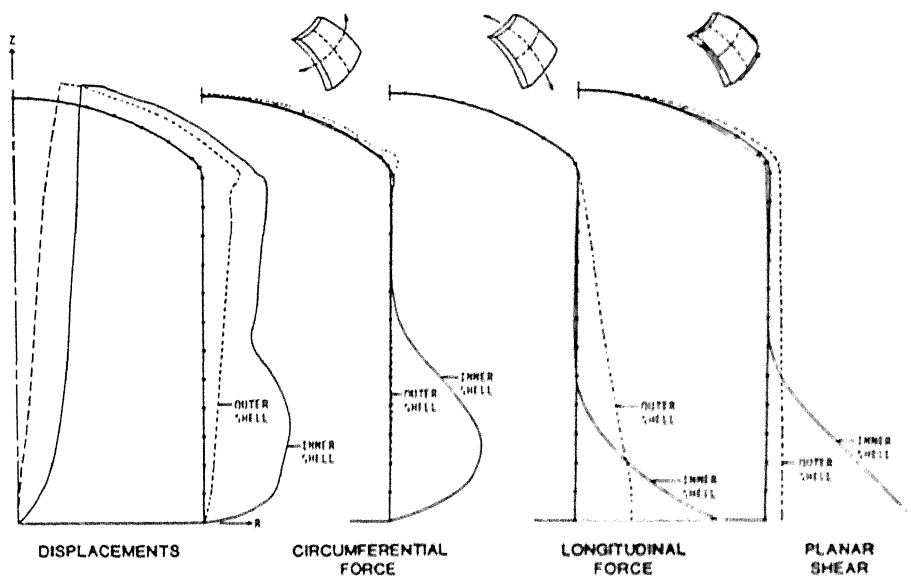


FIGURE 4. SHELL DISPLACEMENT AND FORCE DIAGRAMS

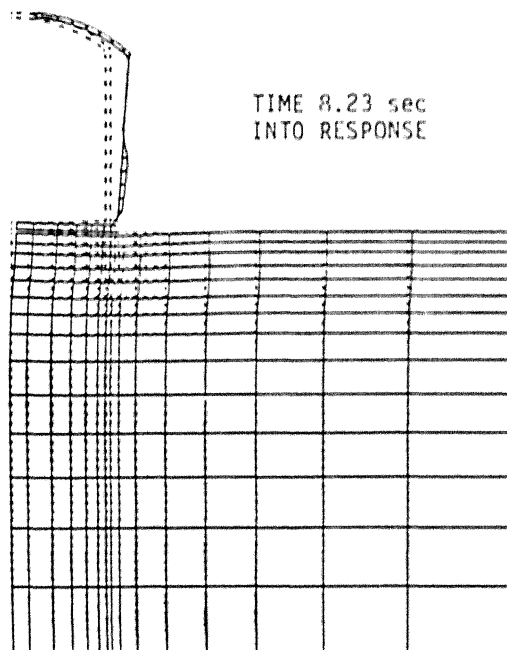


FIGURE 5. DISPLACEMENT OF AXISYMMETRIC FINITE ELEMENT MODEL