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SEISMIC DESIGN OF OIL STORAGE TANKS

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Abstract— In the first part of this paper, provisions from various international codes on design seismic forces for oil storage tanks were reviewed. This paper reviews provisions related with the analysis and modeling aspects. These aspects include mechanical analogue of tank, time period of lateral and vertical mode of vibration, hydrodynamic pressure distribution, sloshing wave height, soil-structure interaction etc. The codes reviewed are: American – API 650 , March 2013, European – EN : 14015 , GSDMA – IITK , Guidelines for the seismic design. It is noted that all the codes use mechanical analogues to evaluate hydrodynamic forces, particularly due to lateral base excitation. The provisions on inclusion of effect of vertical excitation are not covered in all codes. Provisions of soil-structure interaction, buried tanks, flexibility of piping are either not addressed or are given in only qualitative terms. A brief description on limitations in **Indian code is also presented.**

Keywords— Seismic design, Oil storage tanks, Time period, Sloshing wave height, Hydrodynamic pressure

1. INTRODUCTION

In the first part of this paper, provisions on design seismic forces for liquid storage tanks from various international codes were reviewed. In this paper, provisions related with the analysis and modeling of tanks are being considered. Seismic analysis of liquid storage tanks requires special considerations. These special considerations account for the hydrodynamic forces exerted by the fluid on tank wall. Knowledge of these hydrodynamic forces is essential in the seismic design of tanks. Evaluation of hydrodynamic forces requires suitable modeling and dynamic analysis of tank liquid system, which is rather complex. However, availability of mechanical models (analogues) of tanks has considerably simplified the analysis. These mechanical models, convert the tank-liquid system into an equivalent spring mass system. Design codes use these mechanical models to evaluate seismic response of tanks. While using such an approach, various other parameters also get associated with the analysis. Some of these parameters are: Pressure distribution on tank wall due to lateral and vertical base excitation, time period of tank in lateral and vertical mode, effect of soil-structure interaction and maximum sloshing wave height. Design Codes have provisions with varying degree of details to suitably evaluate these parameters.

In this paper, provisions given in various codes on seismic analysis of tanks are reviewed. Codes considered are: American – API 650, March 2013, European – EN: 14015, GSDMA – IITK, Guidelines for the seismic design. The review will in particular focus on following aspects:

i) Mechanical model and its parameters
ii) Hydrodynamic pressure due to lateral and vertical excitation
iii) Time period of tank in lateral and vertical mode
iv) sloshing wave height

2. REVIEW OF CODAL PROVISIONS

Provisions given in: American – API 650, March 2013, European – EN: 14015, GSDMA – IITK, Guidelines for the seismic design will be reviewed. It may be noted that some of these codes deal with only specific types of tanks. It is seen that ground supported tanks are either fixed at base or rest on flexible base. The type of flexible base used and its description varies from code to code.

2.1 Mechanical models

As explained earlier, a mechanical model replaces the tank-liquid system by a spring-mass system, which considerably simplifies the evaluation of hydrodynamic forces. In these mechanical models it is recognized that vibrating fluid inside the container has two components, one that moves in unison with the tank (called impulsive component) and another one which undergoes sloshing motion (called convective component). Various quantities associated with a mechanical model are: impulsive mass (Mi), convective mass (Mc), height of impulsive mass (hi), height of convective mass (hc) and convective mode time period (Tc). It may be noted that heights hi and hc are used when base pressure is not considered. If base pressure is included then corresponding heights are denoted by h'i and h'c respectively. For evaluating the impulsive force, mass of tank wall and roof is also considered along with impulsive fluid mass.

2.2 Time period of impulsive mode

Impulsive mode refers to lateral mode of tank-liquid system. Lateral seismic force on tank depends on the impulsive mode time period. Time period of tank-fluid system depends on the flexibility of support also. Eurocode 14015 has followed the expression given by Sakai et. al. (1984). Eurocode 14015 also gives the expression suggested by Malhotra et. al. (2000) for evaluation of impulsive mode time period. API 650 prescribe a constant value of design spectral acceleration and hence impulsive time period is not needed in these codes.

2.3 Hydrodynamic pressure distribution due to lateral excitation

Stresses in the tank wall depend on distribution of hydrodynamic pressure along the wall height. Housner (1963) had derived the expressions for distribution of hydrodynamic pressure on a rigid tank wall due to lateral base excitation. Impulsive as well as convective components of hydrodynamic pressure were considered. Veletsos (1984) has also obtained the distribution of hydrodynamic pressure on rigid as well as flexible wall. It may be mentioned that flexibility of tank wall does not influence the convective hydrostatic pressure. However, it does affects the impulsive hydrodynamic pressure distribution, particularly for the slender tanks. Evaluation of impulsive pressure distribution in flexible tanks is quite involved and can be done only through iterative procedures (Veletsos, 1984). All the codes use pressure distribution of rigid tanks.

2.4 Sloshing wave height

The sloshing component of liquid mass undergoes vertical displacement and it is necessary to provide suitable free board to prevent spilling of liquid. All the codes, except API 650, give explicit expressions to evaluate maximum sloshing wave height. Eurocode 14015 suggest higher of wave height.

2.5 Soil structure interaction

Provisions for consideration of soil-structure interaction are provided only in NZSEE guidelines and Eurocode 14015. First provision pertains to influence of soil flexibility on time period of tank. Expressions for time period of lateral and vertical mode of tank, including the effect of soil flexibility are provided. These expressions are taken from Veletsos (1984). Secondly, inclusion of soil also increases the damping of the structure. Expressions are also provided for equivalent damping of tank-fluid-soil system.

2.6 Other provisions

Apart from the major issues discussed in previous sections, these codes have also provided provisions on some other aspects though with varying degree of details. All the codes mention that piping attached to tanks should have sufficient flexibility to not to induce large stresses at the joints between the tank and pipe. No quantitative specification is provided on flexibility of piping. However, Eurocode 8 mentions that minimum value of imposed relative displacement between the tank and the first anchoring point of piping can be assumed as $\Delta = \gamma I$ x dg/500; where, x is the distance between the anchoring point and the point of connection with the tank; dg is the maximum soil displacement; and γI is the importance factor. ACI 350.3 and NZSEE guidelines mention about buried or underground tanks. ACI 350.3 suggests use of higher values of response reduction factor for buried tanks. This implies that design earthquake forces for buried tanks will be lower than those for above ground tanks. ACI 350.3 has not given any specific guideline for evaluating dynamic earth pressure. NZSEE guideline provides expressions for evaluating soil pressure, which varies linearly along the wall height. Anchorage requirements for ground supported tanks and other complications involved in unanchored tanks are described in NZSEE guidelines and Eurocode 8. For elevated tanks, AWWA D-100 suggests that convective mode need not be considered. However, ACI 350.3, NZSEE guideline and Eurocode 14015 recommend consideration of convective mode. It may be noted that for elevated tanks, the impulsive mode is governed by the flexibility of supporting tower. NZSEE guidelines suggest that for elevated tanks also, impulsive and convective modes can be treated independently. Other codes have explicitly not stated such an approach for elevated tanks.

3. PROVISIONS OF IS CODES

Indian Standard IS :1893-1984 provides guidelines for earthquake resistant design of several types of structures including liquid storage tanks. This standard is under revision and in the revised form it has been divided into five parts. First part IS:1893(Part 1): 2002, which deals with the general guidelines and provisions for buildings has already been published. Second part, yet to be published, will deal with the provisions for liquid storage tanks. IS 1893-1984 has provisions for elevated tanks only, it does not have any provision for ground supported tanks. In the analysis of elevated tanks, the sloshing or convective component is not considered. These limitations in the provisions of IS 1893-1984 have been discussed by Jain and Medhekar (1993a, 1993b). They have also suggested a set of modifications to be incorporated in the provisions of IS 1893-1984, on seismic analysis of tanks. Their suggestions were mainly focused on inclusion of convective component in the analysis of tanks. They suggested separate mechanical models for rigid and flexible tanks. Model of Haroun and Housner (19841) is used for flexible tank and approach of Veletsos and Yang (1984) is used for rigid tank. Impulsive mass calculation suggested by Jain and Medhekar (1993a, 1993b) is along similar lines as that of

NZSEE guidelines (Priestley, 1986). Jain and Medhekar (1993a, 1993b) did not provide any suggestion on response due to vertical excitation. Sloshing wave height expression is also not included.

4. DISCUSSION

Presence of hydrodynamic forces requires special considerations in the seismic analysis of liquid storage tanks. Invariably all the codes use mechanical models (analogues) to evaluate hydrodynamic forces. These mechanical models evaluate impulsive and convective masses, time period of impulsive and convective modes of vibrations, hydrodynamic pressure distribution and sloshing wave height. It is noted that separate mechanical models are available for tanks with rigid and flexible walls. Rigid tank models are much simpler than flexible tank models. As far as evaluation of impulsive and convective mass is concerned, there is no significant difference in the values obtained from rigid and flexible tank models. Recognizing this fact, all the American codes, viz. ACI 350.3,API 650, AWWA D-100, D-110 use rigid tank models to evaluate impulsive and convective mass in all types of tanks. Time period of tank-fluid system, for which close form expressions are available, depends on tank flexibility. Such an approach makes these American codes much simpler as compared to Eurocode 14015 and GSDMA seismic design guidelines. In Eurocode 14015 and GSDMA seismic design guidelines, separate mechanical models are used for obtaining impulsive mass of rigid and flexible tanks. However, Eurocode 14015 does mention *Review of Seismic Analysis of Liquid Storage Tanks IITK-GSDMA-EQ04-V1.0 12* about procedure of Malhotra et. al. (2000), which is common for tanks with rigid and flexible tanks. It is also interesting to note that API 650 and AWWA D-100 which deal with ground supported cylindrical steel tanks, recommend a constant value of design spectral acceleration for all types of tanks. Hence in these codes there is no need to evaluate time period of tank. The type of base on which tank is resting influences the time period of tank. Some of the codes deal with tanks with different types of base supports.

For example, ACI 350.3, AWWA D-100 and AWWA D-110 mention about anchored, unanchored, flexible and unconstrained type of base supports. Whereas, API 650, Eurocode 8 and GSDMA seismic design guidelines do not describe such base supports. Similarly it is noted that rectangular tanks are considered only in ACI 350.3, NZSEE guidelines and Eurocode 8. Provisions on response to vertical base excitation have been given with varying degree of details. All the AWWA codes, specify the maximum value of hydrodynamic pressure due to vertical excitation in term of fraction of those due to lateral excitation. However, API 650, Eurocode 14015 and GSDMA seismic design guidelines provide more rational approach for evaluating hydrodynamic pressure due to vertical excitation. They suggest evaluation of time period of breathing mode of vibration (axisymmetric mode), based on which design acceleration value can be obtained. Distribution of hydrodynamic pressure along the tank height is also provided in these codes. It is noted that Eurocode 14015 has provisions to consider the influence of wall flexibility on hydrodynamic pressure due to vertical excitation. API 650 does not have any provisions to consider effect of vertical base excitation. Except API 650, all codes have provisions to evaluate maximum sloshing wave height. GSDMA guidelines suggest consideration of higher convective mode while evaluating sloshing wave heights. All other codes consider only first sloshing mode. Eurocode 14015 and API 650 mention higher values of sloshing wave height . *Review of Seismic Analysis of Liquid Storage Tanks IITK-GSDMA-EQ04-V1.0 13* As far as elevated tanks are concerned, AWWA D-100 does not recommend consideration of convective mode in the analysis of elevated tanks. However, API 650, Eurocode 14015 and GSDMA guidelines do recommend consideration of convective mode in the analysis of elevated tanks. It may be mentioned here that ACI 371 which exclusively deals pedestal supported elevated tanks also mentions that convective mode need not be considered if fluid weight is more than 80% of total weight of tank. GSDMA guidelines also suggest that for elevated tanks, impulsive mode, which is largely governed by the flexibility of supporting tower, and convective mode can be treated independently.

Indian code IS 1893-1984 is quite ill equipped to provide any suitable seismic analysis of liquid storage tank. It has no provision for tanks resting on ground. The provision on elevated tank also does not considered convective mode of vibration. Recognizing these limitations Jain and Medhekar (1993a, 1993b) have given a set of suggestion to modify IS1893-1984. They have largely followed the approach of NZSEE guidelines and have suggested use of separate mechanical models for rigid and flexible tanks. Further, Jain and Medhekar (1993a, 1993b) have not given any provision for response due to vertical excitation. Expression for sloshing wave height is also not given by them. The review presented in this paper will be helpful in further improving the suggestions of Jain and Medhekar (1993a, 1993b).

5. CONCLUDING REMARKS

Review of various codes revealed that API 650 which is the most recent code, is quite comprehensive and simple to use. In this code parameters of mechanical model are evaluated using rigid and flexible tank model. The flexibility of tank is considered in the evaluation of impulsive time period. In contrast to this, Eurocode 14015 and GSDMA seismic design guidelines use separate models to find parameters of rigid and flexible tanks. Such an approach makes these codes more cumbersome to use, without achieving any significant improvements in the values of parameters. Effect of vertical ground acceleration is considered in *Review of Seismic Analysis of Liquid Storage Tanks IITK-GSDMA-EQ04-V1.0 14* various codes with varying degree of details. In API 650 codes, hydrodynamic pressure due to vertical acceleration is taken as a fraction of that due to lateral acceleration. API 650, Eurocode 14015 and GSDM seismic design guidelines suggest more rational approach to obtain hydrodynamic pressure due to vertical acceleration, which is evaluated based on time period of breathing mode of vibration. All the codes suggest, quite similar expressions for evaluating maximum sloshing wave height. For Indian code IS 1893, the provisions for seismic analysis of tanks suggested by Jain and

Medhekar (1994a, 1994b), need to be modified. These modifications are particularly needed to include simplified mechanical models for flexible tanks, to include the effect of vertical acceleration, and to include simple expressions for sloshing wave height.

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