7th International Conference on Seismology & Earthquake Engineering
18-21 May 2015

THE EFFECT OF LONG-TERM CORROSION ON DYNAMIC BEHAVIOUR OF UNANCHORED STEEL CYLINDRICAL TANKS

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Keywords: Unanchored Steel Storage Tanks, Corrosion, Dynamic Behaviour, Imperfections, Dynamic Properties

ABSTRACT

In this paper, long-term corrosion effects on dynamic characteristics of unanchored steel cylindrical tanks are investigated. The corrosion effect is considered as thinning of the upper and lower parts of the wall over time. Dynamic analyses are performed on three different models with different wall thicknesses and height to diameter ratios of 0.4, 0.63 and 0.95 using ANSYS finite element software. In the analyses, the tank's liquid is considered to be crude oil with a level at 90% of the height of the tank. The tank's base is unanchored and without any constraint and is in contact with the foundation through the effect of its weight. For determining the tank dynamic characteristics, including natural frequencies and the corresponding mode shapes, the models are analyzed using linear modal analysis. Comparing the natural frequencies of the corroding unanchored tanks with those of the non-corroded tanks reveals reduction in the stiffness of the tanks due to thinning effects of corrosion. The results of investigations also indicate substantial influence of long-term corrosion on the mode shapes of the tank. As the tank ages, its mode shapes change to completely different forms. Also, comparing the results of numerical natural frequencies with those of the code-recommended approximate methods shows that the latter approximate solution for natural frequencies presents reasonable results for the short tank (H/D = 0.4). However it errs considerably as the height of the tank is increased.

INTRODUCTION

Land-based vertical cylindrical tanks are one of the most prominent industrial structures used widely in oil and petroleum industries for storing different fluids. Most of the structure of these tanks is located on the ground and usually their bases are directly on concrete foundations or consolidated soils. In unanchored tanks, there is no mechanical connection between the tank and the foundation, and the earthquake-induced base shear of the tank is resisted only by the friction between the tank's base and the foundation.

Steel corrosion is one of the reasons for tank's failure during the utilization of the structure. The tank's service life is generally between 20 to 40 years and in some cases the corrosion phenomenon is detected after 1.5 to 2.5 years (Medvedeva and Tiam, 1998). The American Petroleum Institute states that; approximately 20% of hydrocarbon products lost as leakage are caused by corrosion damage in storage tanks (API Standard 650, 1988). Corroded steel tanks are particularly susceptible to seismic loading as the imperfections caused by corrosion highly amplify the seismic response. Corrosion in steel storage tanks occurs mainly due to the presence of well water, water condensate, atmospheric oxygen and acid gases inside the tank. The atmospheric corrosion of the tank from outside is reported to be less significant (Zagórski et al., 2004). Oil-derivative sediments containing, among others, hydrogen sulfide add to the local acidification of the environment. As a result of the above factors, the sections of the shell most susceptible to corrosion are the lower and the upper parts of the tank wall. Therefore, regarding the state of corrosion, the wall of the tank may be divided into three distinct zones; zone (I) corresponding to the upper part of the wall, which, considering the change in liquid level, may not be in permanent contact with oil and is likely to corrode due to water condensate, atmospheric oxygen and acid gases; zone (II) corresponding to the middle part of the wall which as it is in permanent contact with oil is not susceptible to corrosion and zone (III) representing the lower part of the wall which due to residual water is likely to suffer the most from corrosion. The rate of corrosion in Zone (I) is reported to be around 0.4mm/yr, whereas, that in zone (III) averages around 0.5mm/yr (Medvedeva and Tiam, 1998).

Little is reported on the effects of corrosion on the dynamic and seismic response of steel storage tanks. Watawala and Nash (1983) and Zui and Shinke (1985) reported that initial shell imperfections result in prominence of the higher order circumferential modes in the dynamic response of cylindrical liquid storage tanks. In an experimental investigation, Maheri and Severn (1989, 1992) also reported that due to the initial imperfections in the shell of cylindrical tanks, lower order circumferential wave forms are not excited and that the fundamental mode of shell-liquid system is associated with higher order circumferential wave forms. They found that the higher the shell diameter to thickness ratio, the higher the order of the first excitable circumferential wave form will be. Menos (1987) also investigated the effects of non-uniformity in the shell thickness on the fundamental period of vibration of anchored storage tanks. Virella et-al (2006) also investigated the effects of varying (tapered) shell thickness on the dynamic properties of anchored liquid storage tanks. In a recent work, Dehghan-Manshadi and Maheri (2010) investigated the effects of imperfections due to long term corrosion on the linear dynamic characteristics of anchored steel cylindrical storage tanks. Maheri and Abdollahi (2013) furthered that work by investigating the nonlinear buckling response of anchored steel tanks subjected to earthquake loading.

The objective of this analysis is to further the work carried out by Dehghan-Manshadi and Maheri (2010) on anchored steel tanks by determining the long-term corrosion effect on the natural frequencies and the corresponding mode shapes of unanchored steel cylindrical tanks.

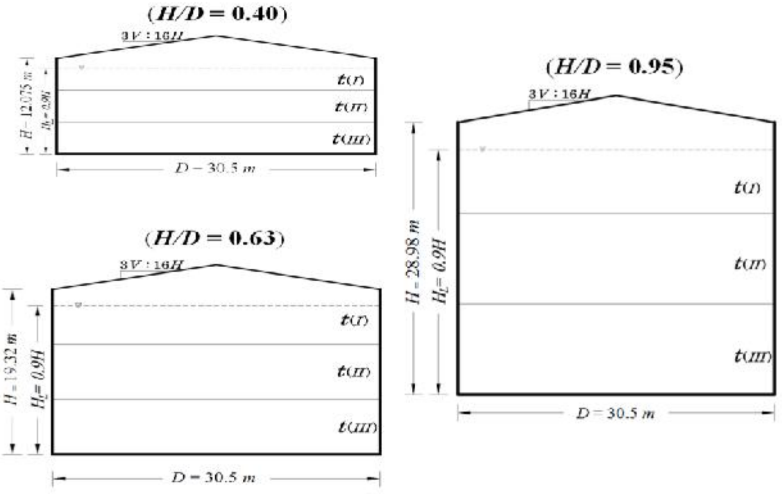

Figure 1. Geometries of the tanks considered [13]

NUMERICAL MODELLING

The tank geometries chosen for investigation are similar to those considered first by Virella et al (2006) and later by Dehghan-Manshadi and Maheri (2010) and Maheri and Abdollahi (2013). The geometries used in this work have height to diameter ratios; *H/D* = 0.40 (Models 1 to 4), *H/D* = 0.63 (Models 5 to 10) and *H/D* = 0.95 (Models 11 to 16), where, *H* and *D* are shown in Fig. 1. The tanks have cone roofs supported by a number of radial beams and columns. In all the models, the tank was assumed to contain liquid to a level of 90% of the height of the tank wall. The only difference between the models considered here and those of reference (2010) is that in this paper the tanks are considered to be unanchored at base.

ANSYS computer program was selected to carry out the numerical analyses. In the FE models, the tank roof system is represented by shell and beam elements. The tank wall is also modeled by shell elements (SHELL63). Shell63 has bending and membrane capabilities. Both, in-plane and normal loads are permitted (ANSYS Manual, 1992). Triangular shell elements are used in the roof and quadrilateral elements are used for the wall. Since the tanks are unanchored, the bottom of the tank is modelled as a plate directly resting on rigid foundation with only horizontal friction connecting the tank base and the foundation. Shell elements (SHELL63) were used to model the tanks base. In total, 11,700 shell elements were used to model each tank.

The hydrodynamic pressure exerted on the shell of a vibrating tank may be of three forms: (i) convective pressure due to the sloshing of the liquid inside the tank, (ii) impulsive pressure due to the rigid body motion of the tank, and (iii) a series of impulsive pressures due to the coupled shell-liquid flexible responses (Maheri and Severn, 1992). For convenience, in the eigen solution, only those modes corresponding to the impulsive modes, in which there is a coupling action between the shell and liquid, are considered in this paper. The more significant convective (sloshing) modes are known to be of much higher periods to interact with the impulsive modes. The eight node solid fluid element (FLUID80), with three DOFs per node, has been chosen to model the incompressible fluid content. The fluid element is particularly well suited for liquid-solid interaction problems. The formulation of the fluid elements is described in (ANSYS Manual, 1992). The liquid mesh has 72,900 elements for all models. Crude oil is used in the computations with a density ρ = 860 kg/m^3 and a bulk modulus K = 1.65 GPa. In order to satisfy the continuity conditions between the liquid and shell media at the wall boundary, the coincident nodes of the liquid and shell elements are constrained in the direction normal to the interface, while relative movements are allowed to occur in the tangential directions.

In the numerical analyses, the time-dependant effects of corrosion is considered as a constant thinning of the upper third and lower third of the wall height at a rate of 0.4mm/yr and 0.5mm/yr, respectively. For the two tank models with aspect ratios of 0.63 and 0.95, different shell thickness configurations, corresponding to; as-new and 5 years, 10 years, 15 years, 20 years and 25 years of thinning, are investigated. For the tank model with H/D = 0.4, due to its small wall thickness, only up to 15 years of corrosion is considered. Sixteen tank-liquid models, thus developed, are introduced in Table 1.

Table 1. Characteristics of the tank models.

Model	**Age (years)**	**(H/D)**	**t(I) (mm)**	**t(II) (mm)**	**t(III) (mm)**
1	0	0.4	10.2	10.2	10.2
2	5	0.4	7.7	10.2	7.7
3	10	0.4	5.2	10.2	5.2
4	15	0.4	2.7	10.2	2.7
5	0	0.63	16	16	16
6	5	0.63	13.5	16	13.5
7	10	0.63	11	16	11
8	15	0.63	8.5	16	8.5
9	20	0.63	6	16	6
10	25	0.63	3.5	16	3.5
11	0	0.95	21.4	21.4	21.4
12	5	0.95	18.9	21.4	18.9
13	10	0.95	16.4	21.4	16.4
14	15	0.95	13.9	21.4	13.9
15	20	0.95	11.4	21.4	11.4
16	25	0.95	8.9	21.4	8.9

To verify the reliability of the numerical models used in this study, modal analyses were performed on the as-new (uniform thickness) short tank-liquid system (H/D = 0.4) and the results are compared with the numerical solution of the same tank by Virella et al. (2006), Dehghan-Manshadi and Maheri (2010) and Maheri and Abdollahi (2013). It should be noted that the short tank model (H/D = 0.4) analysed by Virrela et al. (2006) has a varying thickness shell, whereas, the same tank model analysed by Dehghan-Manshadi and Maheri [10], Maheri and Abdollahi (2013) and in this study has a uniform thickness, averaging the tapered thickness of that given by Virrela et al. (2006), so that the total weight of the shell in all the studies is the same. Despite all the differences in the numerical models considered in the four studies regarding the shell thickness (tapered or uniform), the hydrodynamic effect consideration (added-mass or Lagrangian) and the numerical program used (ABAQUS or ANSYS), results for the fundamental mode of vibration of the tank-liquid system in the four analyses differ by only 2%.

CORROSION EFFECTS ON DYNAMIC PROPERTIES

To evaluate the dynamic properties of tank-liquid models, including natural frequencies of vibration and their associated mode shapes, modal analysis is performed using the Reduced Method [13]. The method uses the HBI (Householder-Bisection-Inverse iteration) algorithm to calculate the eigenvalues and eigenvectors within a specified range for eigenvalues. It is relatively fast because it works with a small number of Master Degrees of Freedom (MDOF). The accuracy of the results depends on how well the mass matrix is approximated, which in turn depends on the number and locations of MDOF. The dynamic response of thin-walled structures such as steel storage tanks is such that; a large number of coupled lateral (*m*) and circumferential (*n*) natural modes may be excited in a specified frequency range. The first mode, which is associated with the lowest natural frequency or the largest natural period (T_{max}), is not usually the most significant mode, i.e. it is not the mode with the highest participation factor. The first natural mode is usually of higher circumferential wave number, whereas, the most significant mode, i.e. the fundamental mode, is generally associated with the first circumferential mode number (n = 1) and possesses the highest modal participation factor. Total number of modes obtained for the short tank (H/D = 0.4) and the tall tank (H/D = 0.96) in both the anchored and unanchored conditions are shown in Fig. 2. It is evident that the unanchored tank has larger number of modes many relating to the base of the tank and indicating a more flexible system. Also the number of modes within a specific frequency range increases with aging as progressive corrosion also causes the tank to become more flexible.

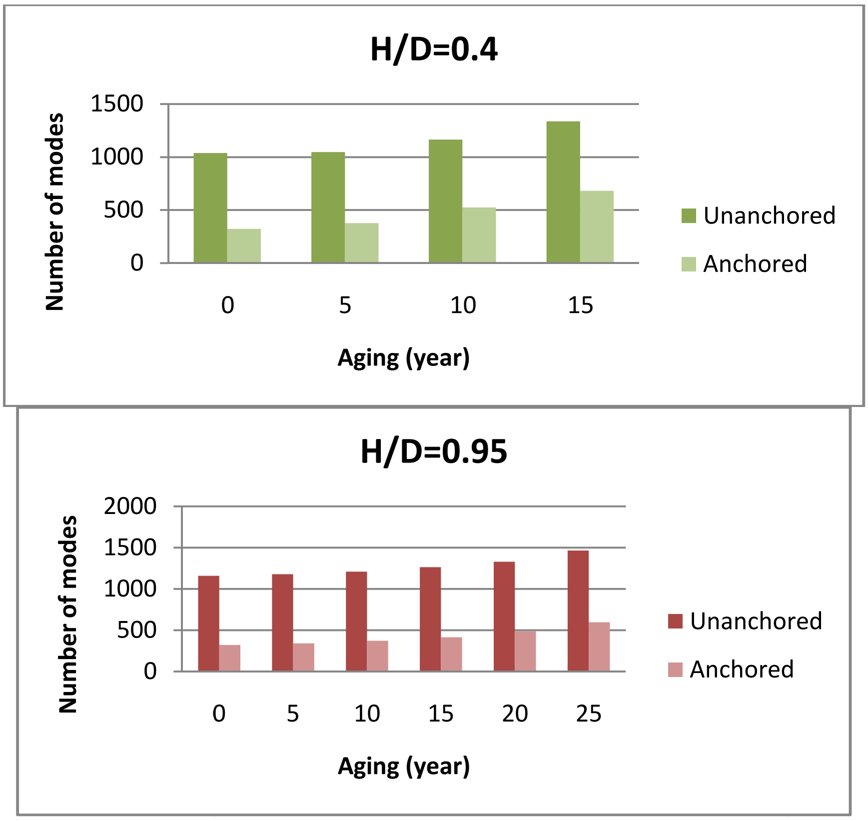

Figure 2. Total number of modes in a given frequency range

NATURAL FREQUENCIES OF VIBRATION

The natural frequencies associated with the first lateral mode (m = 1) having different circumferential (n) wave forms for the three tanks investigated at different states of corrosion degradation (aging) are plotted in Fig. 3. A number of points can be deduced from the data presented in this figure; (i), as discussed, the change in natural frequency with increasing circumferential wave number is not linear, showing that the lowest frequency is not associated with the circumferential wave number n = 1, (ii) the change in natural frequencies with increasing circumferential wave number for the as-new tank is smooth and well-defined; with increasing age and progressive corrosion this trend becomes more irregular and (iii) progressive corrosion with aging results in a general reduction in tanks stiffness and lowering of natural frequencies.

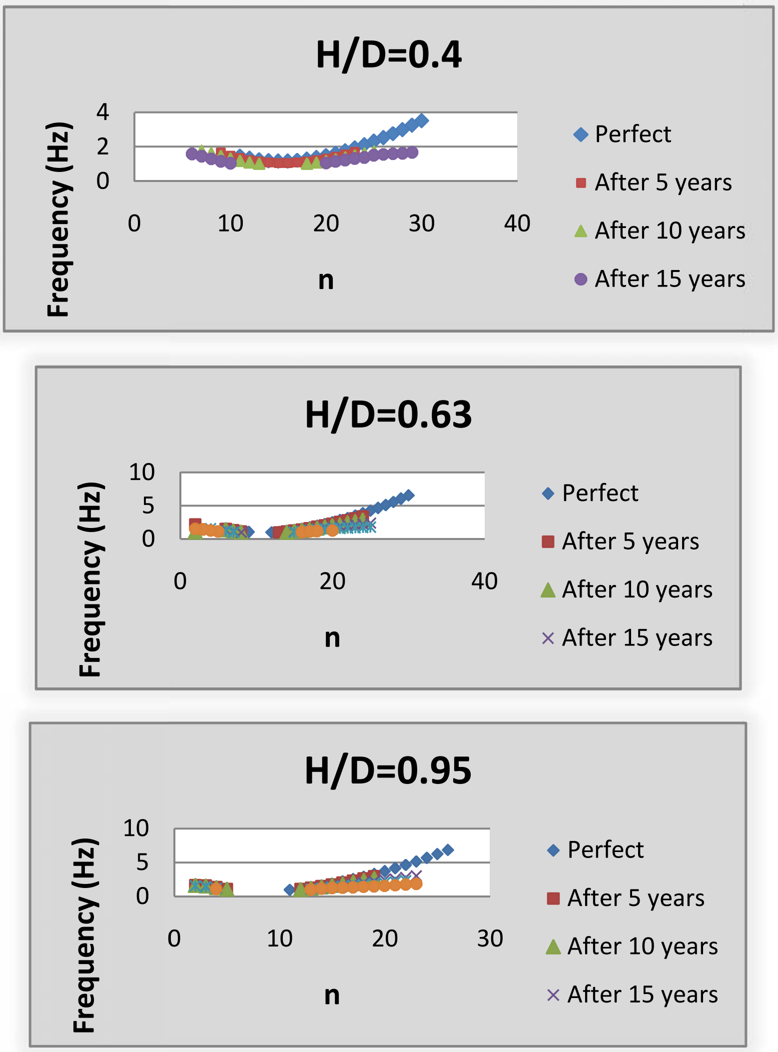

Figure 3. Variation in natural frequencies with changing circumferential wave number (n) and progressive corrosion for the first lateral mode of vibration (m=1)

MODE SHAPES OF VIBRATION

The effect of base fixity on the mode shapes of vibration is as noticeable as their corresponding natural frequencies. A typical comparison is shown in Fig. 4. In this figure, the fundamental modes (m=1, n=1) of the tall tank (*H/D* = 0.96) in both anchored and unanchored conditions are compared. The effect of long term corrosion degradation on the mode shapes of the unanchored tank is also very profound. As a typical example, in Fig. 5 the first mode shape of the short tank (m=1, n=25) for the as-new (perfect) tank is compared with the same mode of the tank after 15 years of corrosion degradation. A marked change in the mode shape can be observed as the lower parts of the corroded tank exhibits larger relative displacements compared to the as-new condition.

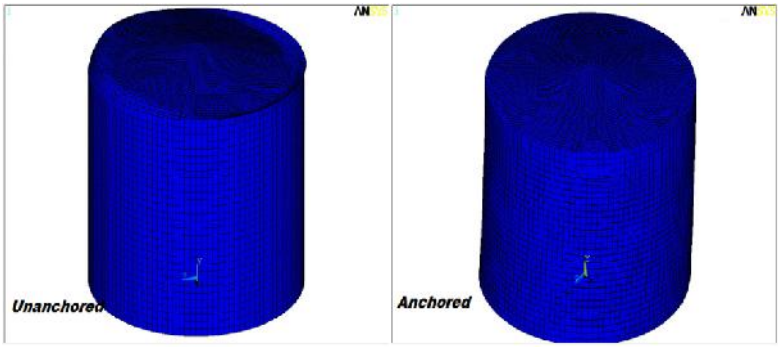

Figure 4. The fundamental mode of vibration of the anchored and unanchored tall tank

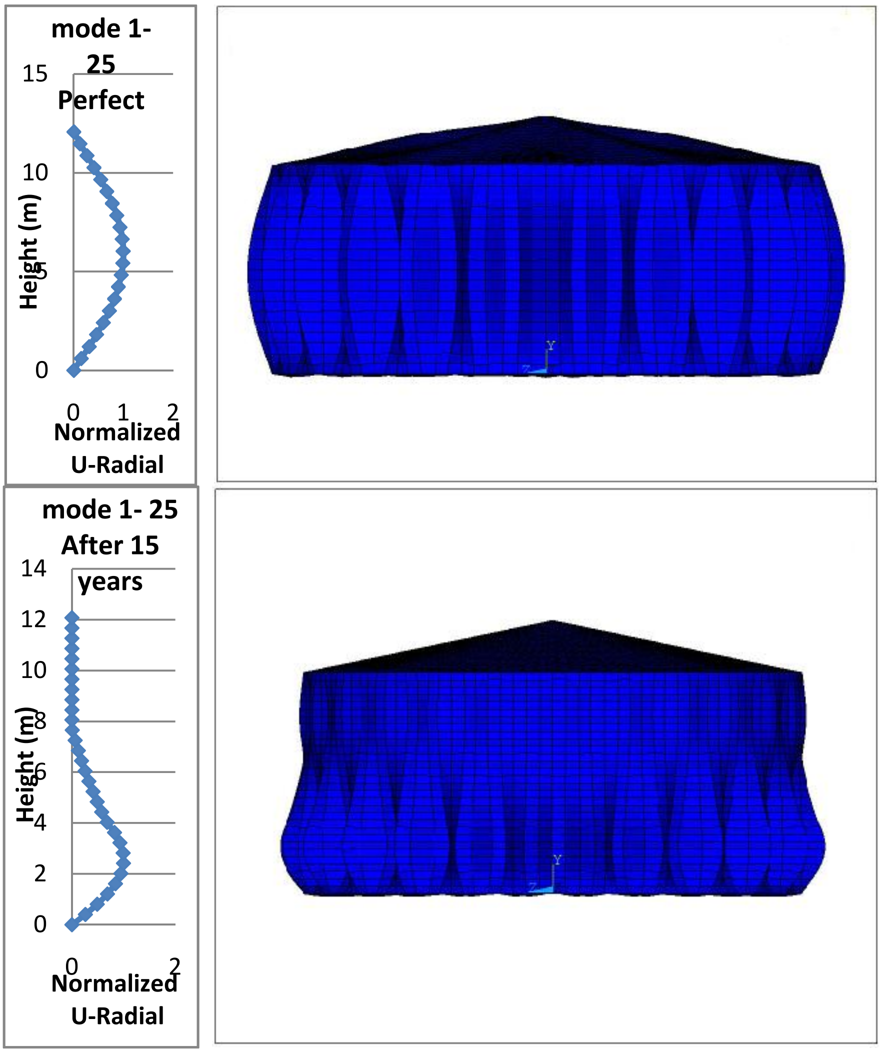

Figure 5. The effects of corrosion degradation on the first mode of short tank

To have a clearer view as to the effect of time-dependant corrosion degradation on the mode shapes of the tanks, the first mode shape of the short tank (*H/D*=0.40) as-new and after 5, 10 and 15 years corrosion is shown in Fig. 6; and those of the tanks with *H/D*=0.63 and *H/D*=0.96, as-new and after 5, 10, 15, 20 and 25 years of corrosion degradation are shown respectively in Fig. 7 and Fig. 8. It can be noted that in all three tanks long term corrosion has a marked effect on the mode shapes; the effect being more profound in the short tank compared with taller tanks.

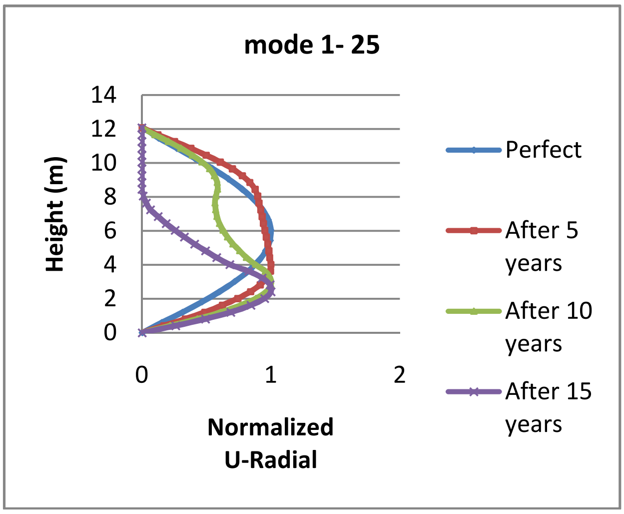

Figure 6. The effect of corrosion on the first mode shape (m=1, n=25) of the short tank (*H/D*=0.40)

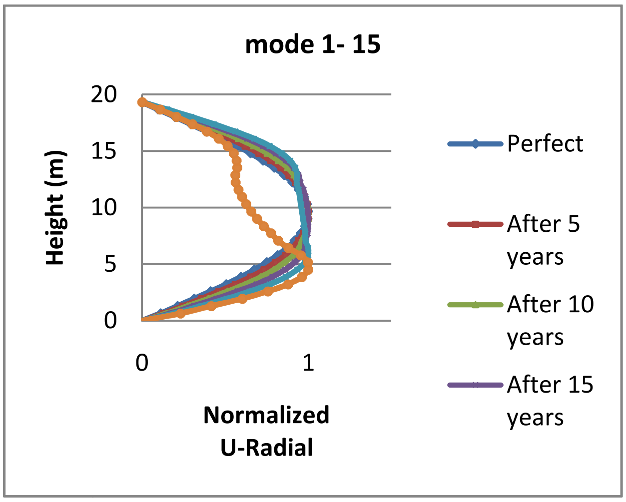

Figure 7. The effect of corrosion on the first mode shape (m=1, n=15) of the tank with *H/D*=0.63

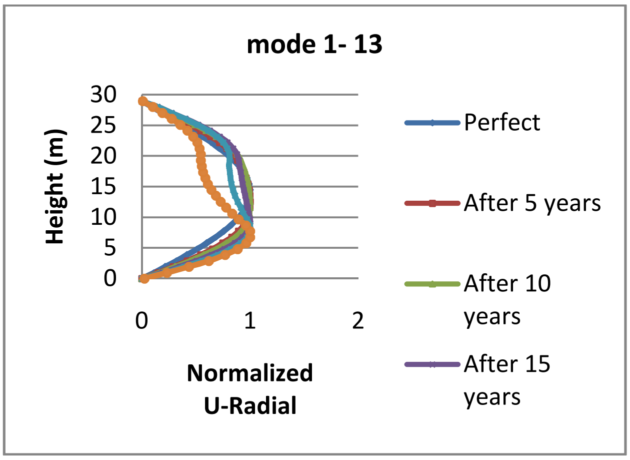

Figure 8. The effect of corrosion on the first mode shape (m=1, n=13) of the tall tank (*H/D*=0.95)

CONCLUSIONS

Results of the numerical investigation presented in this paper on the effect of long term corrosion degradation on the dynamic properties of unanchored steel liquid storage tanks lead us to the following conclusions:

1- Within a specific frequency range, the unanchored tank has larger number of modes compared to the anchored tank. Many of the excess modes relate to the base of the unanchored tank, however, some relate to the tanks wall indicating the unanchored tanks to be more flexible than the anchored tanks.
2- The number of modes of the unanchored tanks within a specific frequency range increases with aging as progressive corrosion also causes the tanks to become more flexible.
3- The change in natural frequencies with increasing circumferential wave number for the as-new tanks is smooth and well-defined; with increasing age and progressive corrosion this trend becomes more irregular.
4- In all three tanks investigated, the long term corrosion has a marked effect on the mode shapes; the effect being more profound in the short tank compared with the taller tanks.

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