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THE EFFECT OF SHAPE DEFORMATION ON VERTICAL TANK VOLUME METROLOGY BY COUPLED FINITE ELEMENT ANALYSIS

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ABSTRACT

Vertical tank is one of the most important metrology tools for liquid petroleum products in international commercial transaction, and tank shape deformation due to the hydrostatic effect will bring errors for tank volume calibration. One 1000m^3 vertical tank was regarded as analysis object, and finite element model was built. In this computation model, the couple effect between tank bottom and foundation was considered. According to the computation results, the shape deformation of tank was discussed. The radial deformation of tank course increase with the liquid level, and the maximal radial deformation is 2.3mm at lower course. The tank bottom deformation along z axis increased, and the maximal value 3.5mm occurred at the middle of the tank bottom. To ensure the accuracy of vertical tank calibration, it is necessary to correct the model of empty tank according to the tank shape deformation.

Keywords: Volume, Metrology, Vertical Tank, Shape Deformation, Finite Element Analysis.

1. INTRODUCTION

The vertical storage tank is mandatory metrology equipment which is the main measurement and storage appliances of the bulk liquid energy trading settlement. As an important part of the energy systems of the national economy lifeline systems, the vertical storage tank has been used widely, especially in the petrochemical industry [1], and its calibration accuracy is directly related to the domestic and foreign trade, economic interests.

Nowadays, the vertical storage tank volume is measured through geometric measurements in the international community, and its core content is the measurement of the diameter of the vertical tank on each course, which is a basis for the establishment of the cylindrical geometry model to calculate the vertical tank volume table. Specific methods include Strapping method, ORL method and OTM method [2-4]. Most of the measurements are undertaken under the condition of empty cans, then being corrected with static pressure correction formula. However, the liquid level often changes in the vertical tank when it is used, and vertical tank floors with the ground is not based on rigid connection, then the measurement error due to the tank deformation has been technical difficulty.

Dai Hongzhe [5] established the finite element model of the cylindrical tank structure which took the liquid sloshing and lift-off in the bottom of the tank into account, and respectively carried out tank bottom uplift and "elephant foot" deformation analysis under the action of horizontal and vertical load7. Because the traditional vertical tank foundation treatment technology of visualization degree is not high and the lack of precision shortcomings, Hu Min [6] established the vertical tank foundation soil 3D simulation model, and effectively verified it through the actual experiment8. Cao Qingshuai [7] summarized and put together a large number of measured data of all kinds of large storage tank settlement deformation, and used the Fourier decomposition analysis of uneven settlement around tank on tank structure for finite element analysis9. With the long-term observation of the vertical tank foundation surface and deep soil deformation, The above studies are related research of the vertical tank foundation and the contact problems, but the coupling contact analysis of the vertical tank and the foundation is not perfect. This paper attempts to build coupling contact finite element model including vertical tank and foundation cushion, and analyze the deformation of the vertical tank and the foundation. The simulation analyzed the deformation of the tank foundation as a whole in different level cases. The goal is to gain the effect of volume measurement of vertical tanks of different course radial deformation and floor Z direction deformation. The finite element model provides a new method for overall analysis of coupling contact deformation of the vertical tank and foundation.

2. THE ESTABLISHMENT OF FINITE ELEMENT MODEL OF VERTICAL TANK AND FOUNDATION

As shown in Fig.1, the vertical cylinder storage tank with radius R is fitted with liquid (height is H_W and the mass density is ρ_1). The oil storage tank is placed directly on the foundation which consists of asphalt sand layer and sand stone cushion layer. With the effect of oil pressure within the tank, the pressure is sufficient to enable flexible bottom of the storage tank plate to generate partial deformation. Coordinate system is shown in Fig.1.

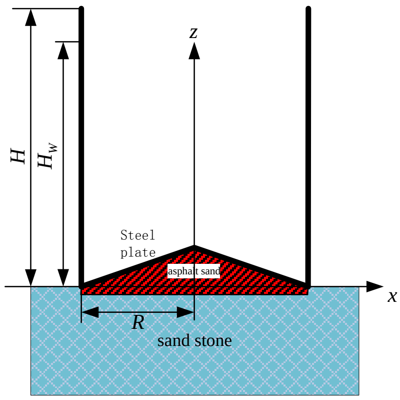

Figure 1. The tank structure and the geometric coordinate system

Taken a 1000m^3 vertical tank as analysis object, the diameter of the Clough short tank model this paper establishes is 12m, and the height is 8m. The thickness of tank wall varies as the direction of height increases, as shown in Table1.

Table 1. The thickness of tank wall

Height(m)	Thickness(mm)
$h\leq 2$	6
$2<h\leq 6$	5.5
$h>6$	5

The tank wall uses the cylindrical plate to connect at different depth. The plate density is 7.8×10^3 kg/m^3, and the elastic modulus is 2.06×10^{11} N/m^2, and the Poisson's ratio is 0.3. Considering material nonlinearity, bilinear hardening model is adapted, and yield strength is 215MPa, and the tangent modulus is 2.06×10^9 N/m^2. Conical steel plate taper in the bottom of the tank is 0.1%, and the thickness is 5mm. The other material properties are in the same with the tank wall. The density of oil stored in the tank is 0.8×10^3 kg/m^3. Taking the liquid compressibility and viscosity into account, the elastic modulus is 2.04×10^9 N/m^2, and coefficient of viscosity is 0.00113 Ns/m. There is asphalt sand cushion of which the thickness is 0.1m in the tank bottom plate，and the elastic modulus of cushion was preliminarily decided as 6.8×10^8 N/m^2, and Poisson ratio 0.2. There are coarse sand stone cushion below and around, of which the length and width are 36m, depth 2m, and the elastic modulus of cushion was preliminarily decided as 6.8×10^8 N/m^2, and Poisson ratio is 0.2.

2.1 The contact element simulation

The foundation cushion in finite element model of the bottom of the tank foundation cushion is a conical with slight taper, and the bottom is steel plate with the same taper. Targel70 and Contal74 elements in Ansys face to face contact are used to simulate the contact surface of the tank bottom and foundation cushion. The two units can simulate large sliding and large deformation with friction, providing coordination and stiffness matrix calculation, no rigid surface shape restrictions, allowing for multiple model control, such as binding contact, initial permeability gradient. The CONTA174 unit is 3D 8 node quadrilateral element with high order, which can be used for a node in the 3D entity or shell element. TARGE170 is also used in 3D use cases; the target surface shape can be described by triangle, cylindrical surface, conical surface, spherical and the control node10.

Face to face contact calculation model is based on the following formula

$$\begin{aligned} C_s &= C_p \times M_u \\ C_p &= C_T \times F_{kn} \\ F_{kn} &= M_u \times P_{res} / S_{lto} \end{aligned} \tag{1}$$

Where C_s, C_p, C_T are the contact friction force, the contact pressure and contact penetration value between the tank bottom and foundation cushion respectively; F_{kn}, M_u, P_{res}, S_{lto} are the normal contact stiffness, friction coefficient, contact pressure and maximum slip factor of the contact element respectively. Based on the above equation, it is derived that the friction coefficient M_u and normal stiffness F_{kn} control the contact force, and whether the definition is correct or not is the key to decide whether the contact calculation results are reasonable or not.

2.2 Contact surface mesh and node coupling

The calculation of face to face contact element is with large amount. In order to ensure the accuracy and convergence, it is needed to control that the number of nodes is proper. The method used in this paper is to divide the nodes of the tank bottom and foundation cushion into consistent numbers, so that the tank bottom nodes are respectively corresponded to the foundation cushion top node, thereby automatically coupling, which gives convenience for contact calculation, improves the calculation speed, and ensures the calculation precision. With comparing by calculating, the four arcs in the circumferential direction are divided into 20 equal parts in the end portion of the canister, which is the same in the tapered ridges.

2.3 The establishment of coupled contact pairs

In the contact model of tank bottom and foundation cushion boundary, the tank bottom boundary is regarded as the target surface. The base layer is regarded as a contact surface, and the two surfaces together are called a pair of contacts, using Targe170 and Conta174 to define the 3D coupling contact pairs. One important thing in the establishment of coupling contact pairs is to ensure the node number sequence for the target face, because it defines the main contact direction. For the bottom of the tank and foundation cushion 3D contact problem, target triangle unit should make rigid surface normal direction to the contact surface, and the normal is defined with the right hand principle. The contact normal defined by different target surfaces should be consistent; otherwise there will be a problem that the contact pairs cannot be matched, which will result in failure when solving contact problems. The friction coefficient of contact pairs Mu is 0.2, and the algorithm for contact problem is the MPC algorithm.

To sum up, in the finite element model, the bottom plate and the tank wall are discrete as shell element SHELL63; the liquid in the tank dispersed as 3D fluid unit FLUID80 which is based on simplification of Housner model; foundation gravel uses second-order tetrahedral element SOLID92; the contact part of asphalt sand layer and bottom of the tank adopts CONTACT174 and TARGET170 unit. The finite element model is shown in Fig.2.

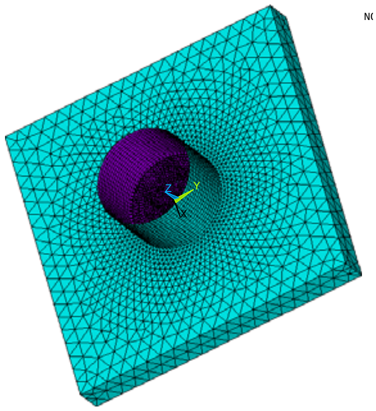

Figure 2. The finite element model of the tank and ground coupling contact analysis

3. THE OILTANK AND FOUNDATION COUPLING CONTACT ANALYSIS

The tank and ground deformation under the conditions of different level height *h* can be obtained by calculating the above model, and Fig.3 shows radial deformation of the tank in the direction of the tank wall (namely the *xoy* plane).

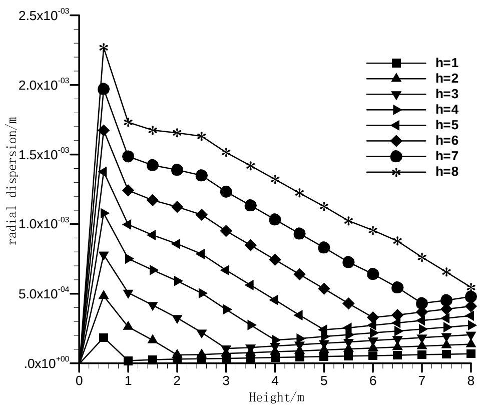

Figure 3. The radial deformation along the height of the tank wall

From the Fig.3, it can be drawn that with the increasing of the loading of oil, the deformation in the vertical tank wall height direction changes in the law of increasing first and then decreasing, and the radial deformation also increases. When the oil is loaded into h>3m, the deformation of the tank more than 2.5m is linear. The calculation results shows the radial deformation of ring plate at the bottom of the tank is the maximal (2.3mm), which should be taken in account to do correction in the calculation of the vertical tank liquid capacity. On the other hand, according to the regulations of international recommendations OIML R71 and ISO7507 1, generally the first ring plate is regarded as the reference circle location, while most of the base circle measurement is carried out under the conditions of empty tanks. Therefore, the correction of the value of the radius of the circle plate must be taken into account during the actual liquid load capacity measurement.

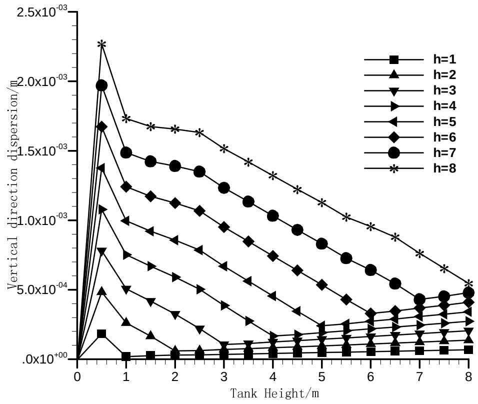

Figure 4. The deformation in the *z*-direction of the tank bottom

The downward sedimentation diagram of the bottom of the tank in the *Z* direction is shown in Fig.4. It can be drawn that with the increase of level, the deformation in *Z* direction of vertical tank bottom increases gradually. Especially at the centre of the tank bottom, the maximum deformation occurs, and the deformation reaches 3.5mm when the level is 8m. In theoretic model, the floor board is regarded as rigid material so that it doesn't has deformation during vertical tank capacity measurement, so the deformation in the *Z* direction will bring certain capacity error. On the other hand, since the edge of the tank wall is connected with the bottom of the tank, the deformation is minimal. Thus, it is suitable to be selected as liquid level measuring reference point, but there will still be 1.8mm level measurement error at the level of 8m because of the deformation in the *Z* direction of the tank bottom. Therefore, in the vertical tank capacity metrology, it need to carry out the error correction resulted from the deformation of the tank bottom.

4. CONCLUSIONS

One 1000m^3 vertical tank as example, the finite element model of a vertical tank and foundation cushion coupling contact is established, and some conclusions can be drawn from the calculation and analysis:

(1) With the increasing of the level, the deformation in the vertical tank wall height direction changes in the law of increasing first and then decreasing. The radial deformation also increases. The radial deformation of course at the bottom of the tank is the maximal, and the maximum value is 2.3mm, which must be taken in account to do correction in the calculation of radius of the reference circle and the vertical tank liquid capacity.

(2) With the increase of level, the deformation in the *Z* direction of vertical tank bottom increases gradually. Especially at the center of the tank bottom, the maximum deformation occurs, and the deformation reaches 3.5mm

when the level is 8m. Therefore, in the vertical tank capacity metrology, it need to carry out the error correction resulted from the deformation of the tank bottom.

(3) The finite element model provides a new method for the overall analysis of the coupling contact deformation of the vertical tank and foundation, which can provided theoretical support for error correction of volume measurement of vertical tanks.

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