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AN INVESTIGATION ON THE STACK VIBRATIONS AND GEOTECHNICAL REHABILITATION SOLUTIONS CASE-STUDY: KHANGIRAN GAS REFINERY

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ABSTRACT

The 75 (m) high stacks of the sulfur recovery units of Khangiran Gas Refinery in Iran exhibited significant levels of vibration in winds. Field observations reported that vibration occurred in the stacks 9 times during reel years. The longest vibration duration is 8 hours and maximum tip deflection is 1 (m). In most intensive vibration occurrence much amount of water exits from around of foundation and some crack is created in the structure. Stack diameter is 4.57 (m) at the bottom and 3.43 (m) at the top and its total weight is 182.3 (Ton). The octagonal foundation diameter is 14 (m) at the beneath part and 6 (m) at the upper part. The thickness foundation is 0.9 (m) in beneath part and 2 (m) in upper part. Foundation base soil is layered compacted and due to special geotechnical condition, it is saturated during the years.

The paper aim is review of applied geotechnical solutions such as improvement of the soil characteristics by eliminating saturation condition and foundation hardness improvement and changing natural frequency of foundation and stack by changing the mass of them. Also, the other popular solutions are discussed in the paper and finally, effectiveness of applied method is studied.

INTRODUCTION

Khangiran is the major gas field in North East Iran and it supplies gas to North Eastern provinces through Khangiran Gas Refinery. Khangiran sour gas refinery was originally founded in late 1970 decade and commissioned in early 80's. The 75 (m) high stacks of the sulfur recovery units of the refinery exhibited significant levels of vibration in winds. Generally steel stacks have relatively low inherent structural damping. Therefore, excessive top-of-stack deflection can result at critical wind speeds due to vortex shedding.

The subject of stack vibrations interests many researchers such as Griffin et al. (1973), Vickery et al. (1975 & 1983), Ruscheweyh (1994), Kawecki and Żurański (2007), Tuominen (2011), Belver et al. (2012), Repetto and Solari (2004 & 2012), Souza et al. (2012), and etc.

Although, the problem of stack vibration is usually investigated in the category of aerodynamics or mechanics of material, but because the problem of stack vibrations of Khangiran Gas Refinery had a geotechnical origin, it is studied as a geotechnical case.

In this investigation, firstly the stack specifications and vibration history is presented. Then, geotechnical investigation precedents and geotechnical specifications of the site are expressed. Next, the stack vibration analysis and rehabilitation solutions are studied, and finally the effectiveness of applied solutions is discussed.

The results of this study show that geotechnical solutions such as soil improvement including dewatering of the site and increasing the stack damping by increasing the stack weight (concrete bracket execution), could reduce the vibration amplitude values till the allowable amounts, but because of oldness of the steel stack and crack occurrence in the stacks, using other solutions would be unavoidable. Therefore, by applying the tuned mass damper (TMD), the stack vibrations are completely reined.

STACK SPECIFICATIONS

The height of four self-support steel stacks of sulfur recovery units (SRU) are about 75 m. The diameter of bottom part (elevation 0-10 m) is 4.57 m, and intermediate part dimension is 4.11 m (elevation 10-21 m). The diameter of upper part (elevation 21-75 m) is 3.43 m. (see figs. 1 &2)

Steel skin thickness is 19.1 mm at the bottom and its amount is 12.7 mm at the height of 37 m and 9.53 mm at the top of stack. Steel material is specified based on ASTM A285 GRADES C. Based on mentioned code; these materials are intended for fusion-welded pressure vessels.

At the lower part, the fireproof brick in the thickness of 15 cm is used as thermal isolation. From the height of 11 m to the top, fireproof cement is used in the thickness of 38 cm. internal stack temperature is 700 centigrade degree and skin temperature in some points measures about 200 centigrade degree. Natural frequency measurements of the stacks show that the amount of this parameter is about 37 rounds per minute, and vertical vibration frequency of the foundation at the end of construction is about 491 rounds per minute. Total weight of each stack is 182.3 ton, so that the weight of steel material, fireproof insulation and the total weight of foundation are about 106.3, 76, and 400 ton respectively. The concrete foundation shape is formed from two octagonal parts which the diameter of internal one and its thickness is 6 m and 2 m, and the diameter and thickness of external part is 14 m and 60 cm respectively.

Fig. 1. Steel stack view

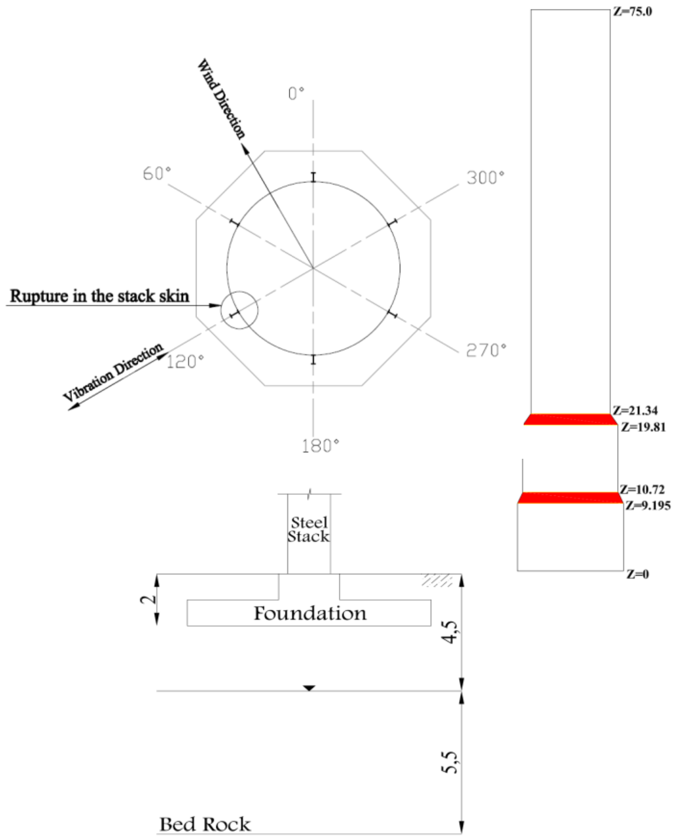

Fig. 2. Geometrical specifications of steel stack and foundation and critical wind and vibration directions

STACK VIBRATIONS HISTORY

Based on registered records, stack vibration problems on the phase one of refinery is referred to construction duration. In winter of 1981, stack vibration occurred for the first time with the vibrations amplitude of about 1 meter while the performance of internal fireproof cements was not completed yet. In the design documents, it had been explained that the allowable displacement has been considered about 35.5 cm.

Second time was at the summer of 1985. The vibrations amplitude has not been recorded properly, but the vibration duration had been about 2 hours. Moreover, much amount of water was splashing out from all around of the stack foundation, during vibration.

The next record, registered in the winter of 1991. At that time, the vibration caused to fail the welded parts of the stack bottom.

Generally, during the years 1981 to 1992, the other vibrations are registered but 5 of them were more severe.

The 6th severe stack vibration occurred at 9th Mar. 1993.

Intense wind velocity is registered for that date. The wind direction, was south to north, while, the vibration direction of stack was east to west. Vibration duration was about 2 hours and maximum tip displacement was about 50 cm and the movement of steel members was observed in the joints obviously.

The 7th severe vibration occurred at 7th Dec. 1993. The vibration duration and the vibration amplitude were about 6 hours and 80 cm respectively. The movement of steel members in the location of joints was more intense and consequently, rupture occurred in steel external skin and the joints. The wind direction was registered similar to four previous vibrations and the vibration frequency was recorded about 37 rounds per minute.

GEOTECHNICAL SPECIFICATION OF THE REGION

Generally, ground investigations shall provide a description of ground conditions relevant to the proposed works and establish a basis for the assessment of the geotechnical parameters relevant for all construction stages. Investigations should also consist of field investigations, laboratory testing, additional desk studies and controlling and monitoring, where appropriate (Eurocode 7, EN 1997-2).

The geotechnical specifications of Khangiran Gas Refinery site have been determined during times using geotechnical investigations done for several purposes. These purposes are as following:

Initial investigation for design of the refinery

These studies were done by Dame & Moore Company and the main goal of that was the detail design of the refinery structures. The investigations were carried out based on exploration excavation including 26 boreholes and 27 test pits and numerous in-situ and laboratory tests. One of important points of this investigation is that the water table was not observed during the exploration excavation. According to the study, soil description is as below:

Upper layer (from ground level to depth of 3.0 m) are classified as loess, which has inherently high strength in the condition of low water content, and strength reduction will be probably in the condition of high saturation ratio.

The second layer (depth 3.0 to 10.0 m) again is loess, with more percentage of sand. But its cementation ratio is more.

The third layer (depth 10.0 to 20.0 m) is stiff silt with clay (the color is green) with high swelling potential. Based on mentioned investigation, allowable bearing capacity of foundations has estimated about 2 kg/cm2, and allowable settlement has been considered 1-2 cm for the refinery structures. Also, the elastic modulus of the soil was assessed about 900 kg/cm2 and the bed rock level was diagnosed almost at -10 m.

Complementary investigation

In order to detailed studies in refinery site, a complementary geotechnical investigation was carried out including 8 boreholes, maximum till the depth of 27 (m) in various parts of the refinery site (15 m in average). Drilling showed that water table was existed between 2 m to 19 m (5.5 m in average).

The existence of a flat non-permeable layer in the depth of 8.0 m to 12.0 m was exactly diagnosed based on these studies. Therefore, despite that the water table was not observed during the drillings of initial geotechnical investigation, because of non-normative sewage disembarkation of the industrial units and official buildings of the refinery and irrigation of site plants, the non-permeable layer has been fully saturated, during times and consequently the water table has rised up till 2.0 (m).

Drainage investigations

Rising the water table in refinery, because of mentioned reasons in last section, provides numerous problems for the refinery structures. Whereas, the drainage studies required some special consideration to decrease the possibility of non-predictable settlements in the foundation due to increase the effective stress, a geotechnical investigation was planned especially for this issue. Therefore, 9 more boreholes are executed in the job site to the depth of 12 m in average.

The results of these studies showed that the underground water layers which its thickness varies between 2.6 to 7.5 m are artesian and it is confined to the loess layer with low permeability from top and consolidated and almost non-permeable layer from the bottom. The permeability coefficient of saturated layer is about 10^{-3} to 10^{-4} (cm/s).

Recent geotechnical studies in the Khangiran Gas Refinery site showed that gypsum layers in the soil of the region are existed too. Hence, the drainage plan had to be done in order to prevent gypsum layers erosion and consequently foundations settlement. In order to gain this goal, firstly the entrance water sources should be closed and instead, an underground sewage transmission system should be executed. Moreover, irrigation system of the site plants should have been replaced by the drip irrigation system.

STACK VIBRATION ANALYSIS

Critical vibration is occurred in the stacks due to Von-Karman vortexes because of the wind on the vertical direction. Strouhal number is the characteristic of this critical vibration as below:

$$S = \frac{Fd}{V} \quad (1)$$

Where, S is Strouhal number (0.2 for critical vibration of the stacks with $H/D > 16$), F is stack frequency, D is stack diameter and V is wind velocity.

Considering mentioned geometrical specifications and natural frequency of the stack, its critical velocity is obtained about 10.8 m/s (or 38.8 km/hr). Moreover, stack vibration theory shows the other phenomenon named “Locking” so that the vibration frequency is not changed (locked) for the velocities more or less than critical amount. In this situation a periodic force impose to the stack in the vertical direction and the amount of that is calculated from following equation:

$$F = 0.5 c_2 \rho_a v^2 \quad (2)$$

Where, c_2 is constant (equal to 0.6 because $H/D > 16$), ρ_a is air unit weight, v is wind velocity and F is stack internal force (per unit area). Considering the stack diameter about 3.5 (m), the stack internal force per unit length of the stack equals to 0.147 kN. Considering that the velocity may reach to 20 m/s in the area of this study and the vibration continues the force in the stack unit length is assumed 0.3 kN/m.

The foundation vibration is calculated from following equation:

$$w = \sqrt{\frac{k}{m}} \quad (3)$$

Where, k is soil strength and m is total weight of steel stack and foundation.

The soil strength parameter (k) is calculated from following equation:

$$k = \frac{AE}{h} \quad (4)$$

Where, A is foundation area, E is elastic modulus of the soil and h is soil depth.

Considering that the thickness of soil layer under the foundation is about 8 m, based on equation number 4, the soil strength parameter (k), at the end of construction duration, was equal to 1539335 kN/m.

Therefore, based on the equation number 3, the foundation vibration obtains about 51.43 rad/sec and the vibration frequency is equal 491 rounds per minutes.

It is considerable that, because the foundation frequency at the end of the construction is 13 times more than critical frequency of steel stack, hence the foundation motion is negligible during the stack vibration.

The other critical vibration is elliptical vibration, which occurs because of low thickness of stack. In the elliptical vibration, the stack section, changes from circular to elliptic. This critical vibration could be calculated by following equation:

$$P = 25. \frac{t}{d^2} \quad (5)$$

Where, t is the thickness of steel stack and d is stack diameter. The amount of this critical vibration for the stacks in the thinnest part is 116.4 rounds per minute which is much more than natural vibration frequency of the stacks (37 rounds per minute). Therefore, it doesn't have any considerable risk for the stacks.

Total weight of the stack can be calculated from the equation below:

$$m = \pi d (h_s \rho_s + h_c \rho_c) \quad (6)$$

The moment of inertia is computed from the following equation:

$$I = (\pi d h_s + \pi d h_c)(\frac{d^2}{8}) = \pi \frac{d^3}{8}(h_s + h_c) \quad (7)$$

Because the stack generally vibrates on 1st mode, the stack displacement equation is:

$$\ddot{z} + 2\sigma w_0 \dot{z} + w_0{}^2 = \frac{F}{M} e^{iwt} \quad (8)$$

Where, w_0 stack natural frequency, M equivalent weight, F stack internal force. Elastic modulus is calculated from the equation below:

$$E = \frac{E_s h_s + E_c h_c}{h_s + h_c} \quad (9)$$

The w_0 is calculated as shown following,

$$w_0 = \sqrt{\frac{\pi^4}{32 l^3} \cdot \frac{E_s h_s + E_c h_c}{h_s + h_c} \cdot \frac{\pi d^3}{8} \cdot \frac{h_s + h_c}{0.228 l \pi d (\rho_s h_s + \rho_c h_c)}} \quad (10)$$

$$w_0 = \frac{n^2}{16} \cdot \frac{d}{l^2} \sqrt{\frac{E_s h_s + E_c h_c}{\rho_s h_s + \rho_c h_c}} \times 2.094269$$

Considering the values of the parameters such as E_s, E_c, ρ_s and ρ_c, the parameter of w_0 will be,

$$w_0 = \frac{n^2}{16} \cdot \frac{3.5}{75^2} \cdot \sqrt{\frac{E_s}{\rho_s}} \cdot \sqrt{\frac{h_s + \frac{E_c}{E_s} h_c}{h_s + \frac{\rho_c}{\rho_s} h_c}} \times 2.094269 \quad (11)$$

Considering that $\sqrt{\frac{E_s}{\rho_s}}$ equals to 5188.74 then,

$$w_0 = 4.170794913 \sqrt{\frac{h_s + 0.1 h_c}{h_s + 0.307 h_c}} \quad (12)$$

And F_0 is,

$$F_0 = w_0 \times \frac{60}{2\pi} = 39.827 \sqrt{\frac{h_s + 0.1 h_c}{h_s + 0.307 h_c}} \quad (13)$$

Considering the stack thickness, the equation results in proper assessment from F_0 and its amount is calculated equal 37 rounds per minute.

And, the vibration amplitude is calculated from the equation below,

$$CL_0 = 0.6, \quad A = \frac{0.5 CL_0 \times 0.364 L}{0.228 M L W_0^2} \times \frac{1}{2\sigma} \quad (14)$$

Where, σ is relative damping of the system,

Assuming that the amounts of parameters w_0, M and σ are respectively equal to 3.87, 182.37 and 0.01, so, the amount of vibration amplitude computes equal to 33.22 cm.

PROBLEM EXPRESSION

According to previous sections, the foundation frequency at the end of the construction was about 491 rounds per minutes.

In order to study on the stack destructive vibrations, the natural frequency of the stack and foundation was measured simultaneously. The measurements showed that the amount of mentioned parameter is changed into about 150 rounds per minutes. Whereas, the soil strength parameter has direct relationship with the square of frequency, then

$$\frac{f_1^2}{f_2^2} = \frac{K_1}{K_2} \quad (15)$$

And consequently,

$$\frac{K_1}{K_2} = \frac{150^2}{491^2} = 0.1 \quad (16)$$

Therefore, due to rise the water table during times and according to presented reasons, soil strength under the foundation is decreased to 0.1 of initial amount. Moreover, rising up the water table was the main reason for decreasing the soil damping and also increasing the probability of liquefaction of second layer (depth 3.0 to 10.0 m). The tests showed that the humidity percent of soil in the influenced area of the stack foundation is about 13.8% at the depth of 0.7 cm and 18.6% at the bottom of foundation. The results showed that the soil was almost saturated at the level of foundation bottom. There are some evidences that indicate the soil compaction is not appropriate. Using related tests, the soil compaction, calculated about 70%. Moreover, the result of grading test showed that the soil under the stack foundation is in the range of liquefiable soils.

Generally, the main reasons of the steel stacks vibration should be analyzed. Whereas, the 1st vibration occurred during construction while the gunite was not completely executed, some assumptions about this vibration imply that due to low weight and consequently low damping of the system and also because there were no temporary guy wires, this vibration occurred.

The other vibrations mainly occurred because of water table rising up. Although, the water table fell down to the level of -4.5 m, but mentioned fluctuation influenced on the soil strength and consequently the stack damping decreased. Moreover, water table rising up increases the probability of liquefaction in the soil under the stack foundation.

REHABILITATION SOLUTIONS

Considering the above expressions and using principals of structural and geotechnical engineering, 2 rehabilitation measurements are presented as below:
- Soil improvement including dewatering of the site especially in the vicinity of steel stack foundation.
- Increasing the stack damping by increasing the stack weight

<u>Soil improvement measurement including dewatering of the site especially in the vicinity of steel stack foundation</u>

Although, applying the drainage solutions, the water table has been stable at the depth of 4.5m, but the soil strength under the foundation of steel stack decreased under the influence of water fluctuations during times. Therefore, the amount of damping parameter decreased, and also because of low compaction percent the probability of liquefaction occurrence increased due to presence of water. Consequently, soil improvement should be considered in order to prevent or rebate the stack vibration. Generally, usage of deep foundations (such as piles) instead of mat foundations would be more applicable in similar site conditions. Moreover, the execution of a cut-off wall, connected with the non-permeable soil layer (bed rock) could be appropriate here. In this case, soil saturation and consequently damping reduction may be preventable. Considering that the two mentioned items was not considered in the design process of the stacks, soil improvement methods must be applied seriously. One of the best and attainable methods of the soil improvement for the region was the plan of site drainage. For this purpose, particularly a geotechnical investigation was executed which is expressed in previous sections. Recognizing the water table condition and specifications of the layers, a drainage plan was presented and implemented. The water table downfall till the depth of 4.5 (m) is the result of implementation of this plan.

<u>Increasing the stack damping by increasing the stack weight</u>

Generally, two procedures were suggested in this case, which are expressed in this section:

<u>Gunite thickness increase,</u> Vibration analysis of steel stack checked in the condition that the thickness of gunite is added to 5 cm, and the results showed that due to increase the thickness of gunite, the damping of system increases, and the vibration frequency decreases. The stack weight increasing will be equal 1.3194 ton, and total added weight is about 100 ton. In this situation, the vibration amplitude decreases to 21 cm and, if the damping increases twice, the vibration amplitude of steel stacks will decrease to about 10 cm.

Applying this method, the refinery operation will encounter with many problems. Because one of the main prerequisites of this method was that the refinery units have to stop their work. So, abundant difficulties might be created. Moreover, many defects, expect from the method of stack gunite modification, due to temperature shocks. Therefore this solution was canceled.

<u>Concrete bracket execution,</u> In order to increase the weight of stack-foundation system and consequently decrease the damping value, a concrete structure was planned to execute all around the stack foundation which its shape is like a "bracket" (Figs. 3 & 4).

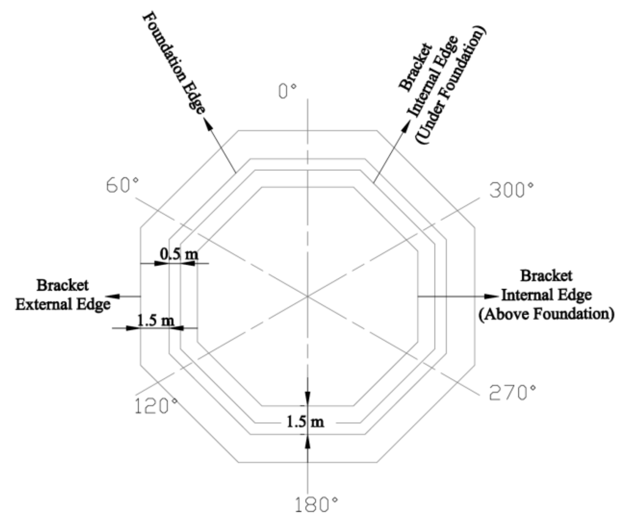

Fig. 3. Concrete bracket plan

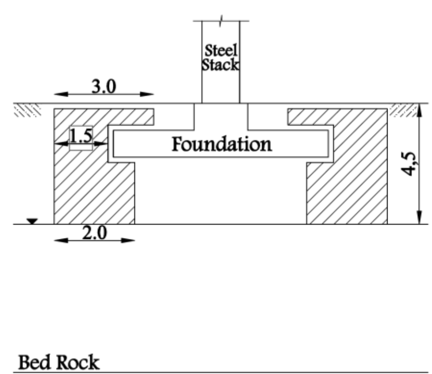

Fig. 4. Concrete bracket section

Upper part length of the bracket is 3.0 m and its lower part length is 2.0 m. So that it covers external edge of the stack foundation from top to bottom. The execution depth of concrete bracket considered at the level of water table (-4.5 m). Concrete bracket was not designed for bearing a specific load therefore it was not necessary to be armed and the concrete grade should be considered at least 300 kg/m^3. The concrete bracket volume is 514 cubic meter and the additive mass to the foundation is about 1200 ton.

It was necessary that the method statement was planned based on staged construction in order to minimize construction hazards such as unallowable and asymmetric settlement of stack foundation. For this purpose, monitoring the water table should be done by a piezometric borehole which is executed in the vicinity of the foundation.

COMPUTATION OF VORTEX-INDUCED LAODS

The load per unit length of the stack due to vortex excitation in the fundamental mode of freestanding stack is given by:

$$w_v = w_0 (z/H)^{1.3} \qquad (17)$$

Where,

$$w_0 = \frac{C_1 q_c D^*}{\left[\beta - \frac{C_2 \phi D^{*2}}{m^*}\right]^{0.5}}$$

Z: Considered height
H: Stack height

$q_c = \frac{1}{2}\phi V_c{}^2$

V_c : Critical velocity ($V_c = f_1 \frac{D}{s}$),

D: Stack diameter (equal to 3.5 m),

m^*: Average mass per unit length for top third of stack ($m = \pi D(h_s \rho_s + h_c \rho_c)$),

ϕ : Air unit weight

f_1 : Frequency

S: Strouhal number

Because $H/D > 16$, then S=0.2 and c_1= c_2=0.6, based on stack specifications and the equations above in the frequency of 37 rounds per minute and the critical velocity is 38.8 km/hr, and q_c equals to 0.0699 kpa. Consequently, the amount of w_0 can be calculated from the equation below:

$$w_0 = \frac{0.1467}{(\beta - 0.0049)^{0.5}} \qquad (18)$$

Where, β is damping value,

Therefore, the stack moment in the foundation level is as below:

$$M = \int_0^H z w_v d_z = \int_0^{75} w_0 \cdot \frac{z^{2.3}}{H^{1.3}} d_z = \frac{250}{(\beta - 0.0049)^{0.5}} \qquad (19)$$

And stack movement is computed from the equation below:

$$EIy = \iint \frac{M}{EI} d_x d_x = \frac{w_0}{H^{1.3}} \times \frac{1}{3.3}\left[\frac{H^{3.3}}{2} x^2 - \frac{1}{4.3 \times 5.3} x^{5.3}\right] \qquad (20)$$

Hence, top stack displacement is calculated from the equation below:

$$\delta = 0.138 \frac{w_0 H^4}{EI} \qquad (21)$$

And, the equation for calculating top stack displacement is:

$$\delta = \frac{0.7907}{(\beta - 0.0049)^{0.5}} \qquad (22)$$

According to STS-1-92, steel stacks have relatively low inherent structural damping which depends on the materials and fabrication techniques used. For example, an all-welded stack has a lower damping value than an all-belted or riveted stack. Additional damping is gained from the inclusion of a lining, soil foundation system and aerodynamic forces, although the last, may reduce the damping.

The damping values shown in table 1 have been absorbed for steel stacks. In general the average value shall be used. However, if the foundation is founded on rock, low stresses piles, or structural framing support, the low damping values shall be used. For support conditions that have inherently large damping or utilize several damping methods the high damping value may be used.

Table 1. Representative damping values for lined welded stacks

Damping Value (β)	0.0032	0.0067	0.010
Status	low	average	high

Other damping values may be used if justified by result of testing or analysis.

As shown, the stack, encountered destructive vibrations in the damping ratio equal to 0.0049.

In the vibration dated 7th Dec. 1993, the vibration amplitude was about 80 cm (totally 160 cm), which is more than 2 times of allowable amount. So based on the equation (22), the damping value is computed equal to 0.0050. Also, based on equation (19), the amount of the moment in the stack toe is computed equal to 18376 kN.m

EFFECTIVENESS OF APPLIED SOLUTIONS

The wind velocity measurements after the installation of the bracket show that the vibration amplitude decreases significantly. Consequently, the amount of damping, increased at least 1.5 times toward previous situation and it changes into 0.0075.

Based on mentioned equations and also the table 1, the displacement of the stack tip is calculated for the damping value of 0.0075. Also, calculation of the parameters such as stack tip displacement, stack internal force and moment are repeated for the amounts of 0.0067 and 0.010 as the lower and upper extreme of damping parameter. The results show in the table 2.

Table 2. Tip displacement, internal force and moment of the stack

Damping Value	Tip displacement	Force per unit length	Moment
β	cm	kN/m	kN.m
0.006	18.63	3.4578	5892.6
0.0075	15.5	2.8770	4902.9
0.01	11.07	2.0542	3500.7

The mentioned calculations are controlled by the method presented by Vickery (1983) and it seems that the results of recent method are more conservative. Moreover, the calculations were checked by Ruscheweyh (1994) and their accuracy is confirmed.

After the modification on the stack foundation including execution of the concrete bracket with the specification presented, the stack motions monitors continuously.

In the 8th and 9th vibrations which are occurred respectively in the dates of 25th Mar. 1997 and 19th Jan. 2000, the vibration amplitude measurements show the amounts which are considerably lower than previous amounts during similar wind situation. The tip displacements of the stack did not exceed from 30 cm in the 8th and 9th vibrations (after modifications).

However, the destructive effects of vibrations during numerous times, caused to occur a serious latitudinal crack equal to 3 m in length in the of second welded conical part of steel stack in May 2002.

Although, the vibration amplitude values had reduced using rehabilitation methods till the allowable amounts, but considering oldness of the steel stack, in order to rein the probable stack vibrations completely, other solutions had studied.

The rehabilitation suggestions to eliminate the stack vibration are categorized as below:

Stiffness methods

Guy wire installation, Execution of this solution has not been possible because the lack of enough space to installation of cable foundations. Moreover, the studies showed that the usage of 3 guy wires in the height of 59 m of the stack and the angle of -45 degree causes to change the section of the stack from circular into elliptical shape. So, in order to prevent it, at least 4 cables were required. Hence, mentioned rehabilitation method was completely impossible and canceled.

Stiffener using, In order to increase the stiffness of stack (K-coefficient), stiffener usage was studied and the results showed that this method caused to increase the structure weight till about 50 ton. On the other hand, the existing gunite must be removed and must be executed again after stiffeners installation, which involves many problems from refinery operation point of view.

Damping methods

Tuned Mass Damper (TMD) installation, The installation of Tuned Mass Damper (TMD) leaded to increase the stack weight till about 4 tons, in installation point. On the other hand, reduction of resonant vibration amplitude was about 80%.

Non-flammable isolator, By applying this method, refinery process encountered, with many problems, because the main prerequisite of this method was stoppage of the refinery process. Many defects, expect from the method, due to temperature shocks.

Aerodynamic methods

These methods including Shroud installation, Helical Strakes installation and removing or relocation of ladders, had many execution difficulties. The studies showed that mentioned methods had no considerable priority in comparison with other methods and sometimes, they probably leaded to increase resonance vibration of the structure.

Mentioned solutions were studied in detail from technical and economical point of view, (Considering that, these part of studies, are not in the scope of this paper, the authors did not express them in detail.) and finally, the installation of Tuned Mass Damper (TMD) was selected as the best solution and executed. Moreover, the structural adequacy of steel stack was studied and the influences of previous vibration and related failures, on the stack structure were checked using in-situ tests such as thickness measurement of steel stack body.

CONCLUSIONS

The origin of stack vibrations of Khangiran Gas Refinery and related rehabilitation methods are investigated in this paper. The results of this study show that geotechnical solutions such as soil improvement including dewatering of the site and increasing the stack damping by increasing the stack weight (concrete bracket execution), could reduce the vibration amplitude values till the allowable amounts, but because of oldness of the steel stack and crack occurrence in the stacks, using other solutions would be unavoidable. Therefore, by applying the tuned mass damper (TMD), the stack vibrations are completely reined.

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