Foundation treatment for stopping excessive vortex shedding vibrations of two 75 meter stacks

Traîtement des fondations pour arrêter la vibration excessive de vortex de deux cheminées d'une hauteur de 75 mètres

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ABSTRACT: Two 75 meter high stacks at gas refinery of Iran showed excessive vibrations due to vortex shedding. The amplitude of vibrations reached 80 centimeters during the last vibration episode. Foundation has been on compacted sandy soil. Further due to the rise of the ground water after construction, induced softening and probable liquefaction in the foundation soil. After remedial action, several episodes of high wind speeds have happened in the site the last one lasting for two days and going up to 54 km/hr and passing around the critical speed of 38 km/hr for more than two hours and did not result in vibrations of more than two centimeter amplitude

RESUME: Deux chemineux de 75 meters d'altitude dans un rafinery de gas avait vibrations excessive de vortex. L'amplitude de vibrations attainait 80 centimeters dans la dernier episode. La foundation etâit basee sur la sable compressée. En plus, la monte de l'eau soustrain aprés la construction a abouti a la liquidation probable de la foundation. Apres quelque remedication il y a eu, plusieurs episode de forte wends de vitesse de 54 km/h qui durêait deux jours. La vitesse critique de 38 km/h a dureé deux heurs. L'amplitude pendant ce temps ne depasse pas de 2 centemeters.

1 INTRODUCTION

Vortex vibrations of stacks is an ever occurring problem for tall stacks. An overview of vortex vibration is presented by H. Ruscheweyh 1994. At the critical wind speed, the stacks starts vibrating and sometimes the amplitude of vibrations becomes so high that the steel lining may fail.

Two stacks at a gas refinery in Iran each having a height of 75 meters had long episode of excessive vibrations. During the last episode the amplitude of vibration reached 80 centimeters (160 centimeters double amplitude) and this resulted in rupture of a part of the steel liner.

The soil investigation at the site shows that the upper strata being of loess origin and not suitable for foundation has been removed and sandy soil has been replaced and compacted as the foundation of the stacks.

The rise in ground water brought the sandy soil to saturation and at times of vibration of the stacks, possible softening and liquefaction might have happened.

The analysis showed that the problem of vibration may be due to softened nature of the foundation soil. Thus remedial action of installing a deep bracket around the foundation were undertaken. This action increased the stiffness and the damping ration of the foundation.

After the remedial action , several episodes of winds up to speed of 54 km/h have happened. The critical wind speed of 38 km/hr has been for the duration of more than two hours. The maximum amplitude is below two centimeters. Thus the stacks are stabilized by the remedial action

2 STACK AND FOUNDATIONS

The stack foundation is composed of two octagons, the first having a diameter of 6 meters and the next being of 14 meter diameter. The thickness of the mat for the fist octagon is 2 meters and reduces to 90 centimeters for the second octagon. The foundation weight is 400 metric tons. The soil is compacted sand which has replaced the original loess deposit which was not deemed fit for the stack foundation by the soil consultant

The stack is cylindrical 75 meters high. The diameter starts at 4.57 meters at the bottom. It changes to 4.11 meters at 10 meters and then at 21 meters it reduced to 3.43 meters up to 75 meters. The steel liner is 19.1 millimeter thick at the bottom and at 37 meters reduced to 12.7 millimeters and at 49 meters is again reduced to 9.53 millimeters.

The thickness of the gunnite lining is 15 cm at the bottom. At 9.5 meters it reduces to 63.5 millimeters and at 11 meters it changes to 38.1 millimeter. The total weight of the stack is 182.3 tons having 106.3 tons of steel and 76 tons of gunnite lining.

During vibration the frequency of vibration was measured to be 37 revolution per minute.

3 ANALYSIS

Three different methods were used for the analysis of the stack vibrations. The first method was equivalent cantilever (Kolousek et al 1984), the second method was the steel stacks ASME STS - 1-1992 and the third method is due to H. Ruscheweyh 1994. A brief summary of the methods is presented here.

3.1 Equivalent Cantilever method

The critical wind speed is evaluated by the Strouhal number

$$S = F\,d / V \qquad (1)$$

where S is the Strouhal number taken usually equal to 0.2 and V is the critical wind speed , d is diameter of the stack and F is the frequency of vortex shedding. Now d for the upper 2/3 of stack is 3.5 meters and the frequency is 37 per minute equal to .6167 cycles per second. Then the critical wind speed is evaluated from (1) to be V= 10.8 meters per second equivalent to 38.8 km/hr. The pressure acting on the stack has an amplitude equal to

$$P = C2\,(1/2)\,\rho V^2 \qquad (2)$$

where P = pressure. C2 a constant = .6 , ρ = air density .0012 ton per cubic meter and V is the critical speed = 10.8 meter per second. then P = .042 kpa now the force per unit height of the stack becomes then Pu = .042*d = 0.147 kN per meter. Because of the vortex locking, this force may act up to velocity of 20 meter per second. Thus for calculation purposes the force is taken as Pu = .3 kN/meter of stack

The form of the vibration of the equivalent cantilever is taken as

$$z(t,x) = (1 - \cos (\Pi z/2 l) z(t) \quad (3)$$

where z(t,x) is the motion at time t and depth x and l = the height of the stack. z(t) is considered sinusoidal, then

$$\ddot{Z} + 2 \delta \dot{Z} + W_s^2 Z (F^* / M^*) \exp(i w t) \quad (4)$$

W_s = natural period of the stack and F^* and M^* are the equivalent force and equivalent mass of the stack in the first mode. Now if the mass per length is = m then

$$M^* = 0.228 \text{ m l}$$

$$F^* = 0.364 \text{ l } 0.5 \text{ C1 } \rho V^2 d \quad (4)$$

where C1 = 0,6. Then the amplitude of motion is evaluated as

$$A = .5 \ \rho \ V^2 \text{ d C1 x } 0.364 \text{ l} / (0.228 \text{ m l } W_s^2) * (1/ 2 \delta) \quad (5)$$

$$A = 0.66435 / 2 \delta \quad (6)$$

where A is the amplitude in centimeters and δ is the damping ratio for the stack system.

3.2 STS1-1992 method of Analysis

The American Society of Mechanical Engineering method of stack analysis for vortex shedding is elaborated in STS1-1992 publication under the title of Steel Stacks. In this method of analysis the force per unit height of the stack is calculated by the following formula:

$$W_z = W_o \ (Z/H)^{1.3} \quad (7)$$

where Z is the height. H = total height and W_o is evaluated by the following formula

$$W_o = C1 \ q_c \ d /(\beta - C2 \ \Phi \ d^2 / m)^{0.5} \quad (8)$$

$$q_c = .5 \ \Phi \ V_c^2 \quad (9)$$

$$V_c = f1 \ d / S \quad (10)$$

where d is the diameter of the upper 1/3 of stack, m is the mass per unit length for the same 1/3 of the stack, Φ is the specific mass of the air and V_c is the critical wind velocity. and S is the Strouhal number. for H/d > 16 it is given that C1= 0.6 , C2 = 0.6 and S = 0.2 . For the stack m = 1.8228 ton per meter for the upper one third and the frequency f = 0.6167 Hz . critical velocity is 10.79 meter per second and Φ = 12/1000 then it can be seen that

$$q_c = .5 * 0.00012 * 10.7917^2 = 0.0699 \text{ kPa} \quad (11)$$

Then it is evaluated that

$$W_o = 0.1467 /(\beta -.0049)^{0.5} \quad (12)$$

where β is the damping ratio. The notations are kept similar to the original publications of the reference cited. It should be noted that if the damping ratio approaches .0049 then stack will undergo violent motion.

The M moment at the stack foundation contact is evaluated as

$$M = 250 / (\beta -.0049)^{0.5} \quad \text{in kN meter} \quad (13)$$

and eventually the amplitude at the top of the stack is evaluated as

$$A = 0.7907 / (\beta -.0049)^{0.5} \quad \text{in centimeters} \quad (14)$$

3.3 Analysis method due to H. Ruscheweyh 1994

In this method of analysis, the Amplitude is calculated by the following formula:

$$A / d = k_\xi \ k_w \ C / S_c \ S_t^2 \quad (15)$$

where A = amplitude, d = diameter of stack C = 0.2

$$S_c = m \ \delta / .5 \ \rho \ d^2 \quad (16)$$

and S_t = 0.2 k_w = 0.63 , k_ξ = 0.133 , m=2424 kg/m ρ = 1.2 kg/m3 d = 3.45 therefore

$$A = 3.45 * 0.133 * \ 0.63 * 0.2 * .5 * 1.2 * 3.45^2 /(0.2^2 * 2424 \ * \delta)$$

$$A = 0.425 / \delta \quad \text{Amplitude in centimeters} \quad (17)$$

The damping ratio recommended for stacks of welded steel liner plus gunnite is about as given by STS1-1992 to vary from very low of .0032 to medium of 0.0067 and very high of 0.01. This being the value of β will yield from equation (14) for amplitude of 80 centimeters of the last episode of vibration , the following value :

$$\beta = 0.005 \quad (18)$$

from the equivalent cantilever formula (6) we get

$$\delta = 0.0042 \quad (19)$$

and from the H. Ruscheweyh method (17) it is concluded that

$$\delta = 0.0053 \quad (20)$$

4 RESULTS OF ANALYSIS

The above analysis from three different methods indicated that the damping ratio for the two stacks is very low compared to similar stacks. It is less than the average value as given by STS1-1992 and it is far below the expected value of 0.01 for steel liner with gunnite lining. The fact that the ground water has approached the sand foundation and the probable liquefaction or softening phenomena indicated that there may be problem with foundation and the low value of damping may be from the softness and low damping of the foundation soil. Thus remedial action was considered to stiffen the foundation and at the same time to increase the damping of the foundation.

5 REMEDIAL ACTION:

The remedial action considered of installing a bracket around the foundation of the stack to increase the stiffness and to increase the damping ratio. Also measures were taken by the refinery personnel to stop the rising of the ground water level. The original foundation and the improved bracket are shown in Fig. 1.

5.1 Stiffness and damping ratio of the improved foundation

The stiffness was calculated by the method recommended by Gazetas and his coworkers (1987 till 1992)

$$k_{sur} = (G / 1-\nu) \ I_x^{0.75} \ (L / B)^{0.25} * (2.5 + .5 \ B / L) \quad (21)$$

where 2L and 2B are the equivalent rectangle surrounding the foundation and G is the shear modulus and ν is Poisson's ratio of

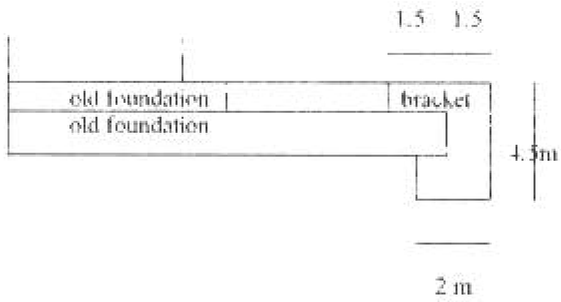

Fig (1) The cross section of the foundation and the bracket

the soil. I_r is the moment of inertia of the contact of the foundation with soil. The above formula gives the stiffness for rocking at the surface. To get the stiffness at depth the following formula will be used

$$krf = ksur\,[\,1 + 1.26\,(d/B)\,(\,1 + d/B\,)\,(\,D/d\,)^{0.2}\,(B/L\,)^{0.5}\,)]\qquad(22)$$

where d is the contact of the foundation edge with soil and D is the depth of the foundation. Then the dynamic foundation stiffness is calculated using the dimensionless frequency of

$$a_o = \omega\,B\,/\,Vs \qquad (23)$$

where Vs is the shear wave velocity and w is the radial frequency.
Using figure 7 of the reference kd is calculated then

$$kdyn = krf * dk \qquad (24)$$

From the soil investigation G = 40500 kPa v = 0.4 and Vs = 150 m/sec. Then for the original foundation the rocking dynamic stiffness is calculated to be

$$kdyn = 6.21 * 10^{[illegible]}\ \text{kN meter/radian} \qquad (25)$$

and for the new foundation with the bracket the stiffness is evaluated to be

$$kdyn = 1.8235 * 10^{5}\ \text{kN meter/radian} \qquad (25)$$

The damping ration is calculated from the formula given by Gazetas and using the Lysmer velocity

$$Vla = 3.4\,Vs\,/\,[\,\pi\,(\,1 - v\,)\,] \qquad (26)$$

Then the Cor coefficient is found from Fig. 3 of the Gazeta's paper and then Cr is found from the following formula

$$Cr = 0.25 + 0.65\,a_o^{[illegible]}\,(d/D)^{[illegible]}\,(D/B)^{[illegible]} \qquad (27)$$

and eventually the damping C is found from

$$C = \rho\,I_o\,[cor\,Vla + cr\,[\,Vla\,(d/B)^{3} + 3\,Vs\,d/B + Vs\,(\,d/B)$$
$$*\,(\,1 + d^{2}/B^{2}\,)]] \qquad (28)$$

The results of the calculation show that for the old foundation the damping C is

$$C = 2.4796 * 10^{[illegible]}\ \text{kN m/sec} \qquad (29)$$

and for the improved foundation the damping C is

$$C = 18.122 * 10^{[illegible]}\ \text{kN m/sec} \qquad (30)$$

The damping ratio is found from the formula

$$\beta = C\,/\,[\,2 * (\,Kdyn * I\,)^{0.5}] \qquad (31)$$

where I is the moment of inertia of the foundation:.
The results are as follows

For the old foundation

$$\beta = 0.2242 \qquad (32)$$

and for the improved foundation the damping ratio is

$$\beta = 0.3528 \qquad (33)$$

Thus it is seen that the following ratios are obtained between the bracketed foundation and the original foundation.

Stiffness ratio = 2.93
Damping C ratio = 7.3
Damping ratio β ratio = 1.6. (3 4)

The above analysis shows that the new foundation has much better dynamic properties than the old one.

5.2 Execution of remedial bracket

The remedial action of installing bracket was done by the National Iranian Gas company under the direction of the second author and with full supervision of the third author.

In order to carry the operation in the safe manner the foundation bracket installation was divided into 24 sections and first the top 15 centimeters of facing concrete was dug with chisel, then excavation was carried out to 4.5 meter and .5 meter of the excavation was carried out under the old footing for tying the two foundations together. This was done for each of the 24 sections in turn and the concreting was carried out (Fig. 2). The total operation took 75 days to complete. The first author was fully informed of the progress of the operation.

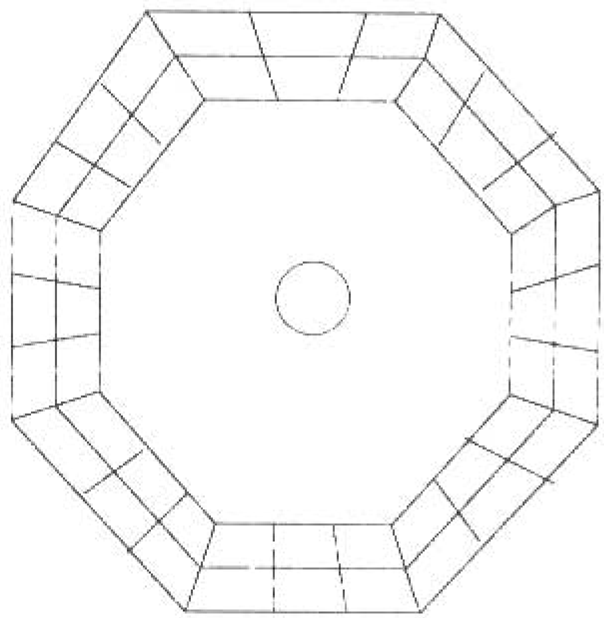

Fig (2) The bracket and the original foundation. Zoning operation

6 STABILIZATION OF THE STACKS AFTER REMEDIAL ACTION

The stacks have been carefully monitored after the remedial action. The weather predication makes it possible to install theodolite at the site and measure the vibration of the top of the stack and video film is also taken to visualize the movement. The several episodes of long and high speed wind has happened at the site. The speed of wind has approached 60 km/hr and the critical speed of 38 km/hr has occurred at times with the duration of two hours. Measurements show that the stacks undergo limited vibration of less than two centimeters amplitude. The stacks thus are stabilized after the remedial action.

7 CONCLUSION

The following conclusions are offered based on the analysis of the results and the measurements.

1. Installing a bracket to sustain the sandy foundation of stacks and to increase the damping ratio and the stiffness is an effective improvement for the reeducation of the vibration of stacks due to vortex shedding if the foundation soil shows signs of softening.

2. The different analysis procedures yield comparative results for the amplitude prediction of the vibration of the stacks due to vortex shedding.

3. The rise of the ground water at gas refineries can create several difficult problems including possible soil softening and liquefaction.

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