VERTICAL EARTHQUAKE LOAD ON CHIMNEYS

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SUMMARY

Horizontal earthquake load has been generally assumed as an important role in damage to structures. It was pointed out by the first author early in 1957 that, damage to chimneys cannot be explained by the action of the horizontal earthquake load at all. Surely, it is induced by the longitudinal wave stress, resulted from the vertical ground motion (1). Preliminary computation of the longitudinal wave stress in chimneys is made in the paper, in order to explain (or with a certain amount of horizontal earthquake load) various damage patterns, especially multiple peripheral cracks. 10 damage patterns of chimneys are analysed and compared, the conclusion is that, the vertical earthquake load but not the horizontal plays an important role in the damage. There are 4 photos in the paper showing that jumping of the damaged section of brick chimneys occurred during earthquake.

10 DAMAGE PATTERNS OF BRICK CHIMNEYS AND THEIR ANALYSIS

1. It is a common phenomenon that inclined cracks and dislocation occurred in brick chimney during earthquake (Photo 1, 2), data on these patterns of damage obtained in the Haicheng earthquake of 1975 are shown in Table 1. Horizontal earthquake loads on sections of brick chimney of different heights are computed, and it is found that the shear resistant capacity of the chimney is much greater than the bending resistant capacity. Because no failure occurs at the critical section, therefore the max. shear at the time of shear failure or dislocation can be computed. In order to make the above conclusion more credible, the computed max. shear value has been amplified to 3, 4 and 5 times for hard, medium and soft soil respectively, denoted as $\tau_{max.}$ in Table 1. Although the max. shear has been amplified, no failure will occur. It is assumed also that chimney suffered the action of large axial tensile stress σ_a at the same time. Shear failure should satisfy the following condition:

$$\tau \geqslant 0.7(\sigma_w - \sigma_a) + R_\tau \qquad (1)$$

where:
- τ - shear stress
- σ_w - compressive stress due to chimney's own weight
- R_τ - shear strength of masonry
- 0.7 - coefficient of friction

If the sign of inequality in equation 1 is replaced by the equal sign and τ replaced by $\tau_{max.}$, then σ_a will be the min. axial tensile stress when failure occurs. Such value is denoted by $\sigma_{a\,min}$ as in Table 1. From Table 1, it is obvious that the vertical earthquake load plays an important role in damage.

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2. Under the action of horizontal earthquake load, bending moment and shear at the top of the chimney are equal to or approach to zero. But damage to the top part of chimney is not scarce during earthquake. In the Haicheng earthquake of 1975, peripheral cracks occurred at the section, about 30 cm from the top of a brick chimney, which was 29 m in height. According to this fact, the max. bending stress at the above damaged section is calculated, about 0.06 kg/cm^2 only. After amplified to 5 times, the max. bending stress becomes 0.3 kg/cm^2 (denoted as σ_{max}), much less than the tensile strength of the section. Occurrence of peripherical crack indicates that the chimney has suffered a great amount of axial tensile stress σ_a and should satisfy the following condition

$$\sigma_a + \sigma \geq \sigma_w + R_\sigma \qquad (2)$$

where: σ - tensile stress in bending moment
R_σ - axial tensile strength of the masonry

If the sign of inequality is substituted by the equal sign, σ is taken as σ_{max}, then the computed σ_a should be the min. axial tensile stress $\sigma_{a\,min}$, which is equal to 0.56 kg/cm . It is seen that the vertical earthquake load is also an important role in damage. Many chimneys which were damaged at the top section are calculated for this purpose, results are not given for every one.

3. Multi-peripheral cracks were often found in the middle or upper part of chimneys during earthquake. In some case, more than 10 peripherical cracks were found in one chimney, min. spacing of which was less than 1 m.

In addition to the falling of the top part, there were many peripheral cracks in the lower part of the brick chimney shown in Photo 3. Bricks around the cracks had fallen down, the chimney was in a danger state.

It is well known that, after the occurrence of the first peripheral crack, no tensile force or bending moment can be tranmitted through the crack. Therefore, under the action of horizontal earthquake load, new peripheral cracks cannot be produced in the sections adjacent to the damaged one. Certainly, this damage pattern cannot be interpreted by means of horizontal earthquake load.

4. Circular chimneys are synmmetric in all directions fundamentally. Under the action of horizontal earthquake load, not much torque will produce in such chimneys. But, during earthquake, spiral inclined cracks sometimes occurred in the chimney or the upper fractured part of the chimney twisted. This damage pattern is hard to illustrate by means of horizontal earthquake load.

Because bending failure of brick chimney only occurs under the action of horizontal earthquake load, therefore the following damage patterns other than those above mentioned, cannot be explained by the horizontal earthquake load satisfactorily.

5. After fractured, the upper portion of the chimney inclined or lay on the remaining portion (Photo 4).

6. By our field investigation, of 100 brick chimneys, the upper portion of which fell down, brick debris scattered uniformly around the base of the chimney with only one exception.

7. Some brick chimneys partly or wholly loosened and cracked during earthquake.

8. Vertical saw-cracks occurred on some brick chimneys.

9. Many peripheral cracks were usually very fine, they can be seen by means of microscope only. But no crushing of mortar in the brick joints occurred.

10. Sometimes a portion of the chimney, located in the central part, fractured (Photo 2), Obviously, it is the result of pounding of the upper fractured portion.

Based on the above analysis, vertical earthquake load is considered as a main factor in the damage to brick chimneys. The same conclusion has been obtained in Ref. (4,5) after the analysis of damage to some other structures.

RELATION BETWEEN LONGITUDINAL WAVE STRESS AND DAMAGE TO CHIMNEYS

Owing to the fact that there is only one or two much more strong waves during earthquake and at the same time, large amount of energy will be dispersed in the process of propagation, therefore, longitudinal wave stress is computed only, which is induced by one or a half strong wave, reflecting twice from the top and once from the bottom during propagation in the chimney. We take this half period or one period wave as harmonic wave.

Let the point of intersection of the two inclined sides of the chimney be the origin of the coordinate axis. Again, let Y and R indicate the distance from the section considered to the top of the chimney and the origin respectively as shown in Fig. 1. Consider the chimney as a truncated hollow cone, the ratio of the inner and the outer diameter of which being constant, then area of the section at y will be proportional to R^2 . So we have

$$F_y = KR^2 \tag{3}$$

Let Z_y and σ_y denote the vertical displacement and longitudinal wave stress of section at y respectively under the action of vertical ground motion, and ρ be density and E , elastic modulus of the material. Then the equilibrium equation will be

$$\left(\sigma_y + \frac{\partial \sigma_y}{\partial R} dR\right) K (R+dR)^2 - \sigma_y K R^2 = \rho K R^2 dR \frac{\partial^2 Z_y}{\partial t^2}$$

Substituting $\sigma_y = E\frac{\partial Z_y}{\partial R}$ in the equation and simplifying, we get

$$\frac{\partial^2 (Z_y R)}{\partial t^2} = C^2 \frac{\partial^2 (Z_y R)}{\partial R^2}$$

$$\therefore Z_y R = f(R+Ct) + F(R-Ct) \tag{4}$$

where C represents longitudinal wave velocity and for brick masonry, it can be taken as 1000 m/sec.

Here the only case considered is that the wave propagates from bottom to top of the chimney and then reflects back, so only the 1st term of equation (4) is used which yields

$$\left.\begin{aligned} Z_y &= \frac{1}{R} f(R+Ct) \\ \frac{\partial Z_y}{\partial t} &= \frac{C}{R} f'(R+Ct) \end{aligned}\right\} \qquad (5)$$

From equation (5) and equation (3), it can be seen that the intensity of the wave is inversely proportional with the square root of the area ratio.

$$\sigma_y = E\frac{\partial Z_y}{\partial R} = \sqrt{E\rho}\,\frac{\partial Z_y}{\partial t} - \frac{E}{R} Z_y = \frac{E}{R} f'(R+Ct) - \frac{E}{R^2} f(R+Ct) \qquad (6)$$

$$\sigma_1 = \frac{E}{R} f'(R+Ct) = \sqrt{E\rho}\,\frac{\partial Z_y}{\partial t} \qquad (7)$$

$$\sigma_2 = -\frac{E}{R^2} f(R+Ct) = -\frac{E}{R} Z_y \qquad (8)$$

Denoting the amplitude of $f'(R+Ct)$ and $f(R+Ct)$ by f'_{max} and f_{max} respectively, the corresponding values of the amplitudes, σ_{1f} and σ_{2f} mentioned above σ_1 and σ_2 respectively at the bottom of the chimney, the corresponding values of σ_1 and σ_2 at section y of the chimney by σ_{1y} and σ_{2y} respectively, we get

$$\sigma_{1f} = \frac{E}{R_f} f'_{max} \qquad \sigma_{2f} = -\frac{E}{R_f^2} f_{max} \qquad (9)$$

$$\therefore\ \sigma_{1y} = \frac{E}{R_y} f'_{max} = \frac{R_f}{R_y}\sigma_{1f} = \sqrt{\frac{F_f}{F_y}}\,\sigma_{1f} \qquad (10)$$

$$\sigma_{2y} = -\frac{E}{R_y^2} f_{max} = \frac{F_f}{F_y}\sigma_{2f} \qquad (11)$$

As a vertical wave propagates from foundation (Concrete, for example, denoted as material 1) to brick chimney (denoted as material 2), its refraction factor β can be expressed as

$$\beta = \frac{2\sqrt{\rho_1 E_1}}{\sqrt{\rho_1 E_1} + \sqrt{\rho_2 E_2}} = 1.6 \qquad (12)$$

Since the area of foundation F_b is larger than that of the base of chimney, so it is assumed that the intensity of wave is increased in proportion to the square root of area ratio.

In order to adopt the same physical quantity as that in horizontal earthquake load, acceleration is also taken as a criterion in calculation. Now, denoting $\ddot{Z}_f$ and $\ddot{Z}_g$ as the max. vertical acc. at the base and the foundation of the chimney respectively, we get

$$\ddot{Z}_f = 1.6\sqrt{\frac{F_b}{F_f}}\,\ddot{Z}_g \qquad (13)$$

Using T as the period of the said half wave, or one wave, the acc. at the bottom of the chimney will be

$$\ddot{Z}_f(t) = -Z_f \cos \frac{2\pi}{T} t \tag{14}$$

(positive for downward direction and negative for upward direction)

From the aftershock records of the Haicheng earthquake, it is noted that the ratio of vertical acc. to horizontal acceleration (denoted as γ_a) ranges from 0.26 to 0.87 with an average of 0.565. Here we take $\gamma_a = 5$ in computation.

Suppose there is a velocity compression wave propagating upward from the bottom of a chimney. Let x be the distance from the end of the wave to the top of the chimney, then the distance from the loop of the following displacement tension wave to the top of the chimney is also x as shown in Fig. 2 (in order to examine clearly, broken line is used to express the wave form in this Fig.).

Energy of the wave will be dispersed continuously along its path of propagation. Suppose 1% of the energy of longitudinal wave is dispersed in every "a" meters in the propagation. As part of its energy will be dispersed when the wave reflects from the top of the chimney, intensity of the wave will be reduced, the coefficient of reduction will be denoted by K_t . When the wave is reflected from the bottom, the coefficient of reduction will be denoted by K_b , thus

$$\begin{aligned}\sigma_y = \sqrt{\frac{F}{F_y}}\,\sigma_{1f}\Big[&-0.99^{\frac{h-y}{a}}\sin\frac{2\pi(x-y)}{CT} + 0.99^{\frac{h+y}{a}}K_t\sin\frac{2\pi(x+y)}{CT} + 0.99^{\frac{3h-y}{a}}K_tK_b\sin\frac{2\pi(2h+x-y)}{CT} \\ &-0.99^{\frac{3h+y}{a}}K_t^2K_b\sin\frac{2\pi(2h+x+y)}{CT}\Big] + \frac{F_t}{F_y}\sigma_{2f}\Big[0.99^{\frac{h-y}{a}}\cos\frac{2\pi(x-y)}{CT} + 0.99^{\frac{h+y}{a}}K_t\cos\frac{2\pi(x+y)}{CT} \\ &-0.99^{\frac{3h-y}{a}}K_tK_b\cos\frac{2\pi(2h+x-y)}{CT} + 0.99^{\frac{3h-y}{a}}K_t^2K_b\cos\frac{2\pi(2h+x+y)}{CT}\Big]\end{aligned} \tag{15}$$

It is very difficult to determine these coefficients, but as a rough estimation, we take K_t = 0.8, a = 3 m. As for K_b , we take it as the reflection coefficient in the wave propagation from brick masonry to concrete, thus

$$K_b = \frac{\sqrt{\rho_1 E_1} - \sqrt{\rho_2 E_2}}{\sqrt{\rho_1 E_1} + \sqrt{\rho_2 E_2}} \approx 0.6$$

Let γ_y denote the ratio of the tensile stress of longitudinal wave σ_y at the y section to the tensile strength. Thus, if $\gamma_y > 1$, the section considered will be failed by the tension of longitudinal wave.

For an earthquake of intensity VIII, where 0.2 g is used as the horizontal acc., the variation of γ_y with x for chimneys of various heights is calculated with T = 0.4 sec respectively. One of the results is given in Table 2. The mechanism of occurrence of multiple-cracks is explained as follows. If only longitudinal stress wave is considered, chimney will be broken by tension at a certain section as the value of γ_y is slightly greater than 1. It is shown in Table 2 that when x=77.5 m, the chimney will be torn by tension at the section 10 meters from the top. After being torn, the tensile force which is larger than the self weight of the torn portion will make the portion jumping upward and reflect from the ruptured section as compression wave propagating up and down respectively. Now let us study the stress condition in the chimney above the ruptured section.

Before the compression wave arrives, if γ_y of a section is greater than 1, this section will be torn apart. From Table 2, it is known that the rupture will occur when x =76 m, γ_8 =1.01. Meanwhile, the distance travelled by the compression wave reflected from the ruptured section is shorter than 1.5 m. It shows that the section at v = 8 m ought to be pulled apart by tension. Again, then x=74 m, γ_6 = 1.02, when x =72 m, γ_4 = 1.002. Therefore, sections at y = 6 m and 4 m may be pulled apart successively. From the above discussion, it is noted that the sections were damaged successively from the bottom within 1/100 sec.

Let's discuss the stress condition below the ruptured section considered. Before the upper torn portion of the chimney falls down, a new free surface has appeared at the torn section. Meanwhile, if the tensile stress resulting from reflection causes γ_y greater than 1 for some sections, then this section will be fractured.

The right column in Table 2 gives the max. values of γ_y of various sections for the chimney under the action of earthquake of intensity VIII. It is shown by these values that the upper part of brick chimney is more easier to suffer damage than its lower part. Field investigation of damage to brick chimneys proves the above conclusion essentially.

Other damages to brick chimneys will be explained chiefly as follows. As a chimney is pulled apart by tension and the upper part above the damaged section is jumping, a small amount of shearing force is capable to cause dislocation; when dislocation is greater than the diameter of the said section, the upper part will fall down on the neighbourhood of the chimney. The higher the upper part jumps, the greater the impact will be induced during its falling and then the bricks will be broken into debris, falling in the neighbourhood of the bottom of the chimney. Projection of debris would occur if horizontal vibration exists. After the impact of the compression wave or the instantaneous impact from the foundation propagates to the top of the chimney, failure may occur over there. Invisible fine cracks may present, if the tensile strength of a certain section is too low, or under the coupling of longitudinal wave and bending moment, the section considered willbe pulled apart. When tensile longitudinal wave stress is rather large, but free section remains safe and is in a state of being pulled, shear and torsion failure will be induced by a little amount of shear and torque. Vertical cracks are liable to occur when the chimney suffers a great amount of compression and if acted by a tensile force in transverse direction combined with thermal stress.

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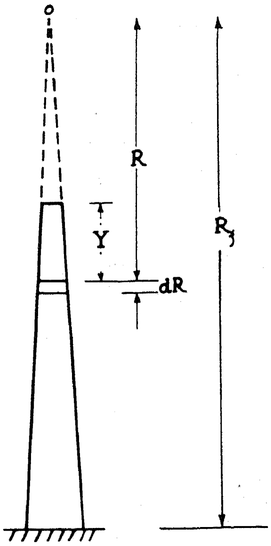

Fig. 1

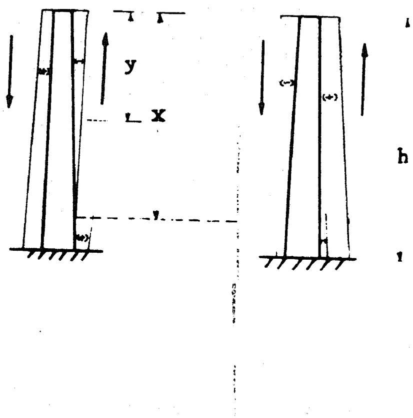

Fig. 2

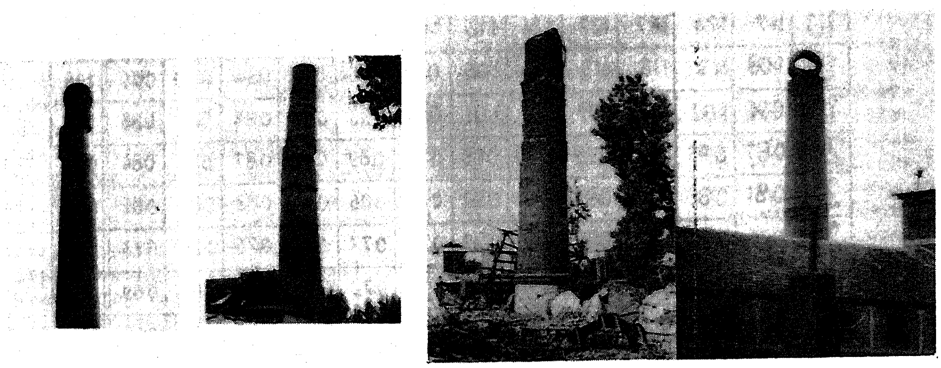

TABLE 1

Location of the chimney	Intensity	Class of Foundation	Height of chimney (m)	Height of the damaged section (m)	Damage pattern	τ_{max}	σ_{max}
Banjia	7	3	38	23	Dislocation	1.10	3.16
Anshan	7	2	30	28	Inclined cracks	0.58	1.17
Saiping	7	2	28	18		0.61	2.65
Yingkou	8	3	20	11		1.00	2.69
Yingkou	8	3	26	13	Dislocation	0.87	2.99
Dashiqiao	9	1	22	17		0.59	2.32
Haicheng	9	1	35	28		0.80	2.41
Haicheng	9	1	25	22	Inclined cracks	0.27	1.68
Tangshan	10	1	35	30	Dislocation	0.75	1.95
Tutian	8	1	35	25		0.82	2.95
Beijing	7	1	24	19		0.55	1.81
Beijing	7	1	24	20	Inclined cracks	0.54	1.84

TABLE 2 Variation of γ_f with x for the 36 m chimney T=0.4sec

X(m)	10	20	30	40	50	60	70	72	74	76	77	77	$\gamma_{f max}$
2	2.06	1.99	1.87	1.71	1.51	1.27	0.99	0.94	0.88	0.82	0.79	0.77	2.6
4	1.65	1.64	1.60	1.52	1.40	1.24	1.058	1.022	0.98	0.82	0.91	0.90	1.65
6	1.42	1.45	1.45	1.43	1.33	1.22	1.09	1.055	1.02	0.99	0.97	0.96	1.45
8	1.27	1.32	1.34	1.32	1.28	1.20	1.09	1.06	1.04	1.01	0.996	0.99	1.43
10	1.17	1.24	1.27	1.27	1.24	1.18	1.09	1.07	1.05	1.025	1.013	1.007	1.27
12	1.08	1.13	1.16	1.15	1.12	1.06	0.97	0.95	0.93	0.91	0.90	0.89	1.16
16	0.96	1.02	1.06	1.07	1.05	1.01	0.94	0.93	0.91	0.89	0.88	0.88	1.07
20	0.87	0.93	0.97	0.99	0.99	0.95	0.90	0.89	0.87	0.87	0.85	0.84	0.99
24	0.81	0.88	0.92	0.94	0.94	0.92	0.87	0.86	0.84	0.83	0.82	0.82	0.94
28	0.76	0.82	0.85	0.87	0.87	0.83	0.78	0.77	0.76	0.75	0.74	0.73	0.87
32	0.70	0.75	0.79	0.80	0.80	0.77	0.73	0.72	0.71	0.70	0.69	0.69	0.80
36	0.65	0.70	0.74	0.75	0.75	0.73	0.69	0.68	0.67	0.66	0.65	0.65	0.75