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Seismic Effect Evaluation for Underground Space & Structures

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SYNOPSIS: It is stressed in this paper that in a strong earthquake the damages of all the underground structures, chambers or any sort of underground space differed quite a lot from that on the ground surface. Numerous evidences show ground motion attenuates immensely downward with depth. However, the earthquake resistance design for underground structures still ignores this fact and sticks to the criteria of ground structures. As a result, very conservative and exhausting design for underground engineering were caused.

Through a series of investigations and based on the comparison between the ground damages and the underground damages of the same site, the authors tried to establish an empirical relationship among the predicted intensity/acceleration for aseismic design, the lithology of ambient strata, depth of embedment and the geometry (width/height ratio) of the underground space/structure. As a conclusion, this paper gives a clear picture of how different the underground damages would be from the ground surface and to what range the ground movement would change due to the existence of underground space directly underneath. This approach might be useful for modifying the criteria of a design earthquake for either ground or underground construction.

BACKGROUND

It has been fully proven by strong historical events that earthquake damages on the ground used to be much more severe than that underground. Fig. 1 shows the meizoseismic area of Tangshan earthquake of magnitude M = 7.8. The earthquake intensity of the epicentral area was investigated and verified as $I_0 = 11$ of the Chinese earthquake scale which is actually equal to Modified Mercalli Scale (MMS). This picture gives an overall view that all the buildings and structures on the ground were totally swept off just like the seven storey hospital building collapsed shown in Fig. 2 in more closer view. However, underground chambers and tunnels of Tangshan undermining directly underneath those totally collapsed buildings even survived with relatively slight damages as shown in Fig. 3 and 4.

The authors would like to point out that such a striking contrast of earthquake damages between on-ground and underground constructions has been observed but very rarely researched so far. Some engineers had no way to approach to a very reasonable methodology for aseismic design of underground constructions. Many of them even put the nuclear burst into consideration instead of seismic loading. Unfortunately, they ignored the big difference between earthquake and nuclear explosion in terms of intensiveness, frequency and time duration of vibration. Because no existing code related to this problem and even there has been no research work practical enough towards such a solution, different engineers take different measures. Some of them did not check earthquake resistance of underground structures to be built in strong earthquake zones, whereas some others may do their aseismic design for underground structures with the same criteria as for those on-ground. Such a big confusion led the design either on the unsafe side or to be conservative otherwise.

FACTORS INFLUENCING THE SEISMIC EFFECT OF UNDERGROUND SPACE AND STRUCTURES

Based on numerous investigations on the underground damages in comparison to the ground damages and also the theoretical analysis (Li & Wang 1988, 1989), the following factors have been recognized to be influencing and decisive to the seismic effect of underground space and structures:

A. The geometry (shape and size) of the underground space and structures;

B. Its depth of embedment;

C. Its lining conditions;

D. The lithology of the ambient formations;

E. The characters of the input wave source.

However, the lining condition and lithology of ambient formation can be considered as the resistant capacity of the structure itself which could be classified into three categories. As for the source character, it is already specified by seismic zonation in terms of either basic intensity (as in China) or equivalent acceleration (as in North America).

(1) The size and shape of underground structures

Evidence shows that the bigger the size, the heavier the damage of the structure. Furthermore, arched or circular cross section is more preferable than rectangular ones. To simplify this factor, a size parameter (S) of the underground structure is specified as the cubic root of the product of its length (L), width (B) and height (h), namely, $S = (L \times B \times h)^{1/3}$.

For linear underground space like tunnels, size parameter should be defined as the square root of its cross section, i.e. $S = (B \times h)^{1/2}$.

(2) The embedment depth of underground structures

It was obviously verified through investigation over seismic events in China that damages decrease with depth of the embedment (d) of underground structures. This is true up to a depth of about 300

Fig. 1. Aerial view of the meizoseismic area of intensity $I_o = 11$ (MMS) of Tangshan earthquake, 1976.

Fig. 2. A seven storey hospital building situated in $I_o = 11$ area totally collapsed. However its underground chamber damaged very lightly.

Fig. 3. An underground chamber stands still (only with very slight cracks) underneath severely damaged area of intensity $I_o = 11$.

Fig.4. The most severely damaged tunnel underneath the area of $I_o = 11$. Actually the only damage was the crack of a thin concrete pavement due to lateral squeezing.

meters. The intensity (I_d) at a certain depth (d) below the ground surface can be estimated with the following statistical formula:

$$I_d = ke^{bd} + I_o \quad (1)$$

where k is a coefficient, I_o is the basic intensity or the actual intensity on-ground; b is a deducing parameter (Wang 1978). In this research, a normalized depth of embedment (d_n) is used which is the ratio of the depth (d) to the height of the structure. Thus, $d_n = d/h$.

(3) The lining and ambient formation condition.

The lining and ambient formation condition can be expressed by a proper classification of underground structures with a practical combination of both factors as follows:

Category I

a) underground chamber in soil with temporary lining;

b) natural cavern in soft rock;

c) simply supported undermining tunnel with fractured top wall

Category II

a) undermining tunnel with face timbering;

b) tunnel, shaft, air raid shelter in soft rock or in stiff soil with brick arch lining;

c) embedded trunk sewers in soil

Category III

a) newly built underground chamber, shelter, station, etc. with reinforced cement lining and/or arching;

b) mining tunnel and shaft with standard face support and lining;

c) natural cavern well modified and strengthened

PREDICTION OF DESIGN EARTHQUAKE INTENSITY FOR UNDERGROUND STRUCTURES

With respect to the specified basic intensity for on-ground structures, the design earthquake intensity for a particular structure at a certain depth below the ground can be predicted.

Based on the case study over 105 underground structures underwent different damages in different earthquake intensity areas from $I_o = 11$ to $I_o = 8$ (MMS) on the ground, a detailed multivariant regression analysis was carried out to predict the underground intensity of a future event.

For more satisfactory correlation and presentation, let the underground intensity of a design earthquake to be predicted is a relative value with respect to the basic intensity or the corresponding acceleration already specified through seismic zonation. It is appropriate to use the normalized intensity, i.e. relative intensity $I_r = I_d / I_o$, where I_d is the design earthquake intensity to be predicted, I_o is the basic or actual intensity on-ground.

The value of I_r also makes sense showing the deduction or attenuation of intensity on-ground down to a certain depth. It is obvious that I_r can be closely correlated with both the embedment depth and size of underground structures. The regression formula goes in the following form:

$$I_r = I_d / I_o = \alpha + \beta f(d) + \gamma \phi(S) \qquad (2)$$

This is a nonlinear regression model. In determining f(d) and $\phi(S)$, 46 cases of underground structures with ambient rock formation of moderate category (B) were studied and tried to fit the correlation. Finally the following regression formula was obtained:

$$I_r = \alpha + \beta / \log(d + 100) + \gamma / S \qquad (3)$$

With particular reference to different ambient formations, we have:

$$I_r = 0.50 + 0.93 / \log(d + 100) - 0.30 / S \qquad (4)$$

for soil strata, very soft and fissured rock formation (category A);

$$I_r = 0.62 + 0.50 / \log(d + 100) - 0.26 / S \qquad (5)$$

for moderate rock formation (category B);

$$I_r = 0.46 + 0.62 / \log(d + 100) - 0.34 / S \qquad (6)$$

for hard and intact rock formation (category C).

ATTENUATION OF UNDERGROUND INTENSITY WITH DEPTH AND SIZE OF STRUCTURES

Knowing the formulae (4), (5) and (6), we may make (S) be constant for a specific size of underground structure to be built at various depth, thus we may rewrite them as follows:

$$I_d = C_1 I_o + 0.93 I_o / \log(d + 100) \qquad (4A)$$

where $C_1 = 0.50 - 0.30 / S$

$$I_d = C_2 I_o + 0.50 I_o / \log(d + 100) \qquad (5A)$$

where $C_2 = 0.62 - 0.26 / S$

$$I_d = C_3 I_o - 0.62 I_o / \log(d + 100) \qquad (6A)$$

where $C_3 = 0.46 - 0.34 / S$.

These equations show that intensity attenuates with the reciprocal of logarithmic depth of embedment.

Similarly, considering the depth of embedment of the structure (d) is known as a constant, we may have,

$$I_d = c_1' I_o - 0.30 I_o / S \qquad (4B)$$

where $C_1' = 0.50 + 0.93 / \log(d + 100)$

$$I_d = C_2' I_o - 0.26 I_o / S \qquad (5B)$$

where $C_2' = 0.62 + 0.50 / \log(d + 100)$;

$$I_d = C_3' Io - 0.34 I_o / S \qquad (6B)$$

where $C_3' = 0.46 - 0.62 / \log(d + 100)$

These formulae show that the intensity attenuate with the reciprocal of the size of underground structures.

Since the normalized intensity (Ir) can be obtained, the predicted intensity of underground structures at a given depth and surrounded by a known category of rock formation will be easily calculated. In earthquake engineering practice, the calculated design intensity can be rounded to integer as it is normally with decimals.

CHECK UP WITH REAL CASES

Very satisfactory check up with tens of real cases of different underground structures ranging from Category I to III were obtained at different areas of ground intensities ranging from 11 to 8, and at different depth of embedment ranging from -3.5M down to -290M, in different formations ranging from A to C categories. For brief illustration, some examples are listed in Table 1.

CONCLUSION

The aseismic design for underground structures needs to be specified with different criteria of intensity from that on the ground. This paper provides a simple method of evaluating underground intensity with respect to the basic intensity officially specified for on-ground construction. Data obtained mainly from Tangshan earthquake which influenced a vast area of tens of thousand square km where hundreds of underground structures were covered. Check up results of this method proved satisfactory. However, more case studies from other parts of the world are necessary to generalize the methodology.

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Table 1. Predicted Underground Intensities Checked up with Real Cases in Tangshan Earthquake (M = 7.8, 1976)

Project	Actual Intensity on ground I_o (MMS)	Depth of Embedment H (meter)	Category of Structure (I, II, III)	Size of Structure $S = \sqrt[3]{L \cdot B \cdot h}$ (meter)	Ambient rock/soil formation (A, B, C)	Actual underground intensity I_{AU}	Normalized Intensity Calculated I_r	Predicted Underground Intensity $I_d = I_o \cdot I_r$
NW Store House	11	1.25	III	4.74	C	9	0.818	9
11th level face No. 6282	11	290.0	II	18.8	A	10	0.909	10
110 Cool Storage	11	77.32	III	11.45	A	8	0.727	8
8th transport tunnel	10	207.58	II	3.05	C	7	0.700	7
2nd level pump house	10	23.31	II	10.98	B	9	0.900	9
2nd chamber	10	19.20	II	6.08	B	8	0.800	8
9671 mining face	9	205.68	II	19.80	C	8	0.889	8
Central pump	9	142.86	III	9.20	B	7	0.778	7
150 pump house	9	37.50	II	4.00	A	6	0.667	6
Tanggu underground path	8	2.1	III	2.04	B	6	0.75	6

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