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A simplified evaluation method for the seismic performance of underground common utility boxes

T. Nishioka & S. Unjoh

Earthquake Disaster Prevention Research Group, Public Works Research Institute, Tsukuba, Japan.

ABSTRACT: This paper presents a simplified evaluation method for the seismic performance of underground common utility boxes (CUBs) with rectangular cross section. Since the seismic deformation of underground structures is primarily the shear deformation in terms of the whole cross section, the proposed method is based on the shear deformation capacity. The shear deformation capacity is studied through the non-linear frame analyses of five types of standard CUBs. In the evaluation method, the seismic performance is checked by the difference between the ground strain criterion and the peak ground strain on the structure's underground level. The proposed method is applied to the CUB located at Kobe in Japan that was subjected to the 1995 Hyogoken-nanbu earthquake. The results show that the CUB has enough ductility with respect to the shear deformation, which coincides with the fact that the CUB suffered only small damage from that earthquake.

1 INTRODUCTION

The 1995 Hyogoken-nanbu earthquake caused serious damage to some of the subway tunnels at Kobe in Japan (Samata 1996). On the other hand, the underground common utility boxes (CUBs) and underground parking structures located at Kobe suffered only minor damage from the earthquake (PWRI 1996). Underground structures had been thought to be relatively safe during earthquakes until the 1995 Hyogoken-nanbu earthquake. It is revealed that they have a wide range of seismic performance according to ground conditions and structural features. In linear underground structures with long distance like lifeline systems, the ground conditions and the structural features generally change. It is necessary for the practical design point of views to simply evaluate the seismic performance of underground structures at a particular site.

The seismic deformation of underground structures is significantly affected by the deformation of the surrounding ground, not by the inertia force acting on the structures. The main mode of the deformation in the whole cross section is the shear deformation. It is reasonable to evaluate the seismic performance of underground structures based on the shear deformation capacity.

The purpose of this paper is to propose a simplified evaluation method for the seismic performance of CUBs with rectangular cross section. The evaluation method is based on the shear deformation capacity of the CUBs. The shear strain transmitting characteristics from free-field ground to the underground structures are applied to the evaluation method.

The shear deformation capacity is studied through the non-linear frame analysis of five types of standard CUBs. The ground strain criterion is determined for the types of the CUBs. Finally, the proposed method is applied to the CUB located at Kobe that was subjected to the 1995 Hyogoken-nanbu earthquake.

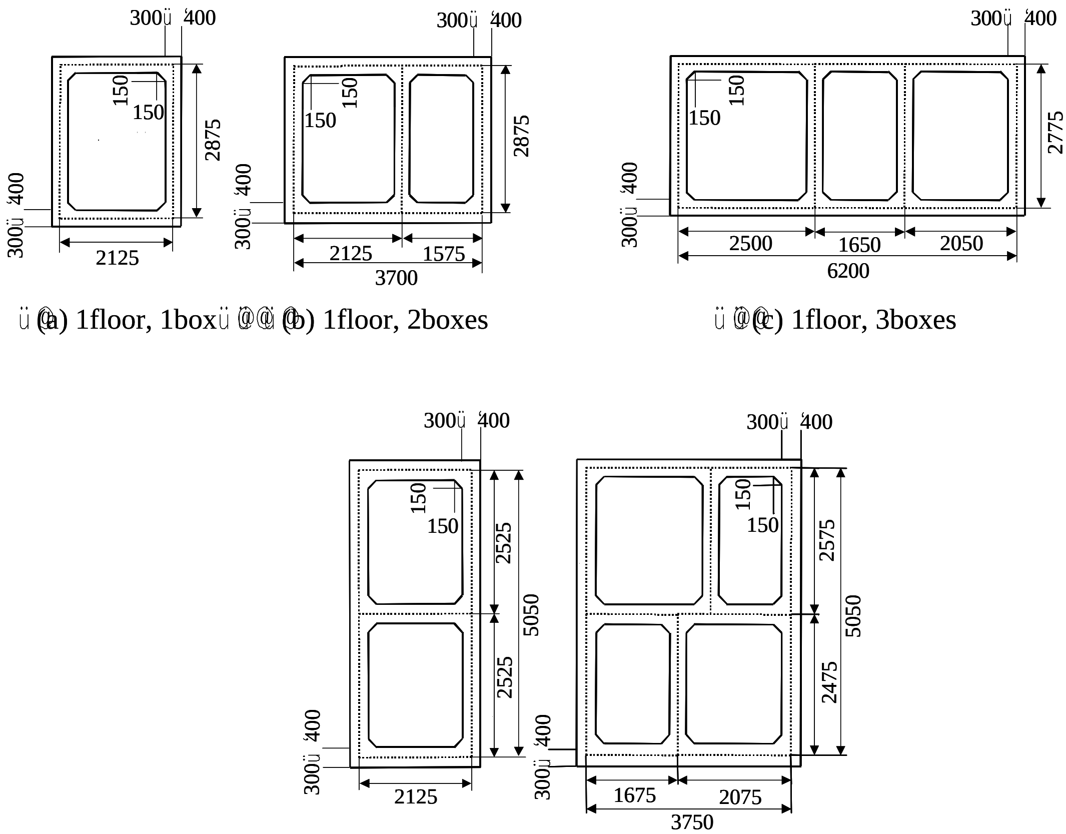
2 ANALYSIS OF SEISMIC DEFORMATION CAPACITY

2.1 Analysis cases

Five types of standard CUBs with rectangular cross section are used for the analysis of the shear deformation capacity. The cross sections of the CUBs are shown in Figure 1. In each cross section, 3 kinds of thickness (d=300, 350, 400mm) of the structural members according to the depths of the CUBs are analyzed. Reinforcements D13, D14, D15 are applied to the thickness d=300, 350, 400mm, respectively. The reinforcements D13, D14, D15 have 13, 14, 15mm diameters, respectively. The combination of the thickness and the reinforcements are based on the existing CUBs. Analysis cases are shown in Table 1. Widths and heights of the cross sections indicate in the center distances of the structural members. Figure 2 indicates the reinforcement bar arrangements. In Section 1, which is around the corners of the cross section, the outside reinforcements are 125mm spacing. The other reinforcements including the inside reinforcements in Section 1 and the reinforcements in Section 2 are 250mm spacing, as shown in Figure 2.

2.2 Push-over analysis

Since the seismic deformation of underground structures is mainly the shear deformation, the push-over analysis to increase the shear deformation is conducted for the evaluation of the shear deformation capacity of the CUBs. The simply-supported non-linear frame model is used for the push-over analysis, as shown in Figure 3. The non-linear frame model has the tri-linear moment-curvature relationships as the concrete crack point, the reinforcement yield point, and the ultimate point. The ultimate point is defined as the point where concrete compression strain reaches 0.0035 (JSCE 1996). Weight per unit volume of the RC, modulus of elasticity, and Poisson's ratio of the concrete are



ü (a) 1floor, 1boxü @@ (b) 1floor, 2boxes ü @(c) 1floor, 3boxes

(d) 2floors, 2boxesü @ (e) 2floors, 4boxes

Figure 1. Cross sections of the CUBs (unit:mm)

Table 1. Analysis Cases

Case	Type of CUBs (Floor, Box)	Width b (mm)	Height h (mm)	Thickness (mm), (reinforcements)	Over-burden (m)
1	1F,1B	2,125	2,875	300(D13)	4.5
2				350(D16)	8.6
3				400(D19)	15.1
4	1F,2B	3,700	2,875	300(D13)	3.7
5				350(D16)	7.9
6				400(D19)	14.5
7	1F,3B	6,200	2,775	300(D13)	1.9
8				350(D16)	3.8
9				400(D19)	7.2
10	2F,2B	2,125	5,050	300(D13)	4.0
11				350(D16)	7.9
12				400(D19)	13.8
13	2F,4B	3,750	5,050	300(D13)	1.0
14				350(D16)	3.4
15				400(D19)	5.4

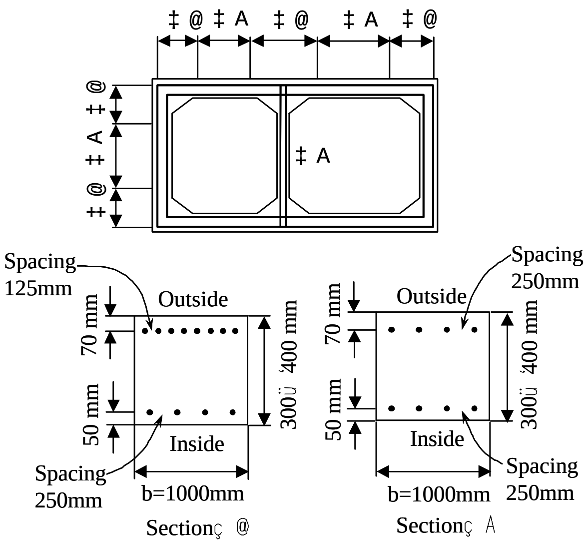


Figure 2. Reinforcement bar arrangements

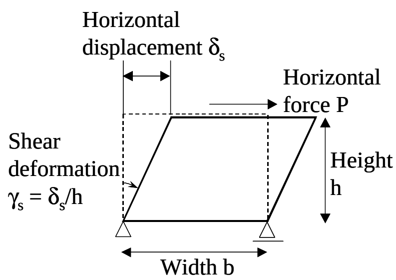
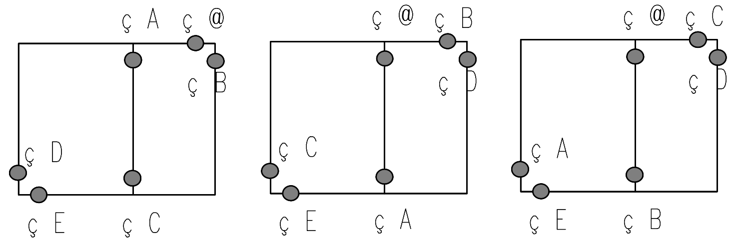


Figure 3. Push-over analysis

assumed as 24.5 kN/m^3, 2.35*10^4 N/mm^2, and 1/6, respectively. The yield stress of the reinforcements is 295 N/mm^2. The thickness of the outside and inside cover concrete is 70, 50mm, respectively. Initial stress of the non-linear frame model is computed under the conditions that the structures are subjected to the over-burden dead load, the horizontal earth pressure at rest, and the ground reaction force to the lower slub.

2.3 Shear deformation capacity

Figure 4 shows the locations and the sequences to reach the ultimate points in Case 4~6. The ultimate points are developed around the bottom left and upper right corners earlier than around the other



(a) Case4 ü@@@@ (b) Case5 ü@@@@(c) Case6

● üLocations to reach the ultimate points

Numbers denote the sequences to reach the ultimate points.

Figure 4. Locations and sequences to reach the ultimate points (Case 4~6)

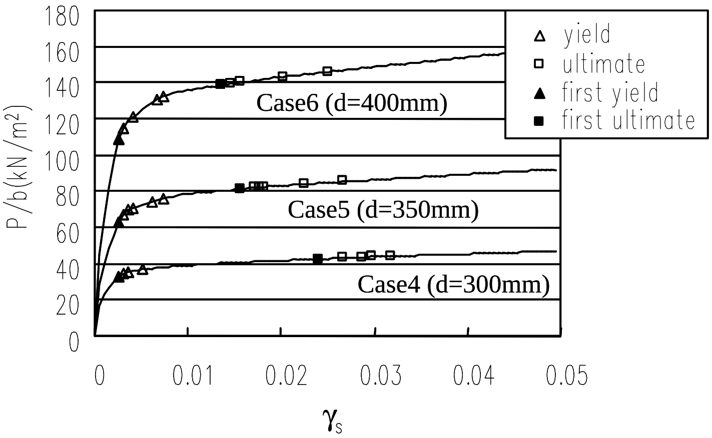


Figure 5. Relationships between γ_s and P/b (Case 4~6)

corners, because the horizontal force on the upper slub is applied in the left-to-right direction from the initial stress condition. Except around the two corners, the ultimate points appear at the upper and lower ends of the partition wall. Case 4~6 have the same locations to reach the ultimate points, but the sequences to reach the ultimate points are not necessarily equal.

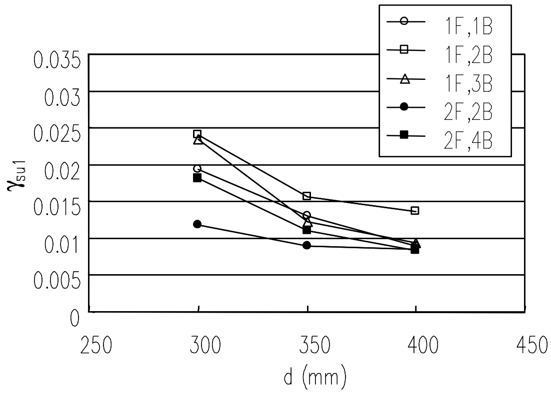
Figure 5 shows the relationships between the shear deformation γ_s and the horizontal force per unit area P/b. The six yield points and six ultimate points are located in the curved lines in Figure 5. The larger the thickness d is, the larger the horizontal bearing force is. There are no significant differences among γ_s at the first yield points, but γ_s at the first ultimate points depends on the thickness d. The other cases (Case 1~3, 7~15) show the same tendency as Case 4~6.

The relationships between the thickness d and the shear deformation at the first ultimate points γ_{su1}, are shown in Figure 6. It is found that the larger the thickness d is, the smaller γ_{su1} is and that γ_{su1} of 1 floor type is larger than γ_{su1} of 2 floors type. The push-over analysis for the opposite load direction (the right-to-left direction) is conducted for the CUBs with the dissymmetric cross section, that correspond to Case 4~9, 13~15. Figure 7 shows the effect of the load directions on the relationships between d and γ_{su1}. Arrows in the legend symbol in Figure 7 denote the load directions. It is found that the load directions do not have much effect on γ_{su1} of the CUBs with the dissymmetric cross section.

As the purpose of the simplified evaluation method is to select vulnerable CUBs that need detailed seismic analysis, the estimation of the shear deformation capacity γ_{sa} of the CUBs should be on the safe side. γ_{sa} is assumed with a safety factor by Equation (1).

$$\gamma_{sa} = \gamma_{sy1} + (\gamma_{su1} - \gamma_{sy1})/\alpha \qquad (1)$$

where γ_{su1} = the less shear deformation at the first ultimate point in the two load directions; γ_{sy1} = the



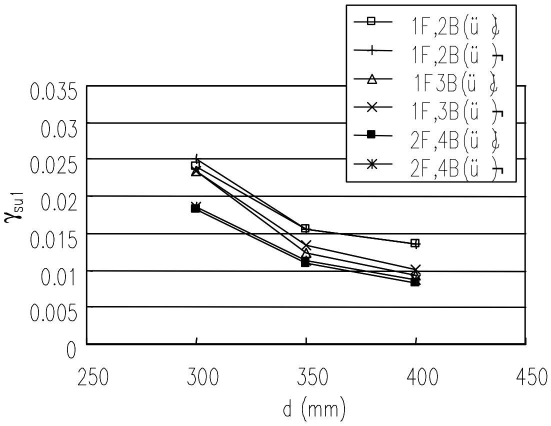


Figure 6. Relationships between d and g_{su1} (Case 1~15)

Figure 7. Effect of the load directions (Case 4~9, 13~15)

Table 2. Shear deformation capacity g_{sa}

γ_{sa}	d=300 mm	d=350 mm	d=400 mm
1 floor type	0.014	0.009	0.007
2 floors type	0.009	0.007	0.006

shear deformation for the same point as γ_{su1} to reach the reinforcement yield; α = safety factor (=1.5). Table 2 shows γ_{sa} that are the minimum shear deformation capacity estimated in each floor type.

3 SIMPLIFIED EVALUATION METHOD

3.1 Ground strain criterion

The authors clarified the shear strain transmitting characteristics from free-field ground to the underground structures (Nishioka et al. 2002). Seismic deformation method (SDM) is commonly applied to seismic design of underground structures, because the deformation of the surrounding ground is a dominant factor for the seismic deformation of the structures. The physical basis of the SDM is explained by static substructure method, which is derived from the dynamic substructure method (Tateishi 1992). Equation of motion of the SDM are given by

$$\begin{bmatrix} K_{SS} & K_{SI} \\ K_{IS} & K_{II}+K_{I0}^{G} \end{bmatrix}\begin{Bmatrix} r_S \\ r_I \end{Bmatrix} = -\begin{bmatrix} M_{SS} & 0 \\ 0 & M_{II} \end{bmatrix}\begin{Bmatrix} \ddot{r}_S \\ \ddot{r}_I \end{Bmatrix} + \begin{Bmatrix} 0 \\ K_{I0}^{G}\cdot r_I^{F} \end{Bmatrix} + \begin{Bmatrix} 0 \\ q_I^{F} \end{Bmatrix} \quad (2)$$

where K = stiffness matrix of the structure, M = mass matrix of the structure, r = displacement vector. The subscripts $_I$ and $_S$ denote the nodes on the soil-structure interface, and the remaining nodes of the structure, respectively. The superscript dots denote time derivation. K_{I0}^{G} = ground impedance matrix, r_I^F = free-field ground displacement vector, q_I^F = free-field ground internal force on the soil-structure interface.

The second row of Equation (2), the equilibrium on the soil-structure interface, is expressed as

$$(K_{IS}\cdot r_S + K_{II}\cdot r_I) = -M_{II}\cdot \ddot{r}_I + K_{I0}^{G}\cdot (r_I^F - r_I) + q_I^F \quad (3)$$

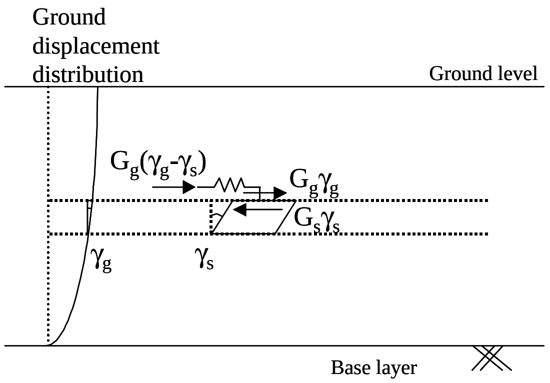


Figure 8. Equilibrium of one-dimensional shear stress

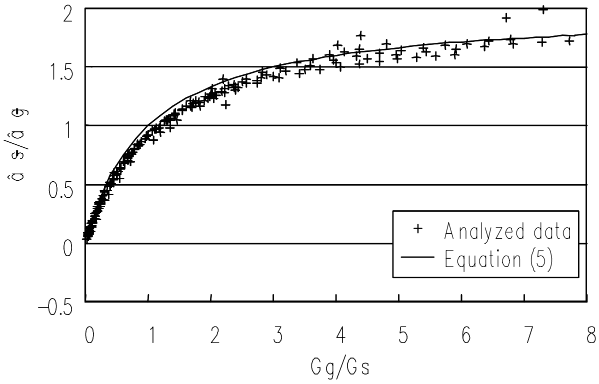


Figure 9. Comparison of Equation (5) and the analyzed data of g_s/g_g

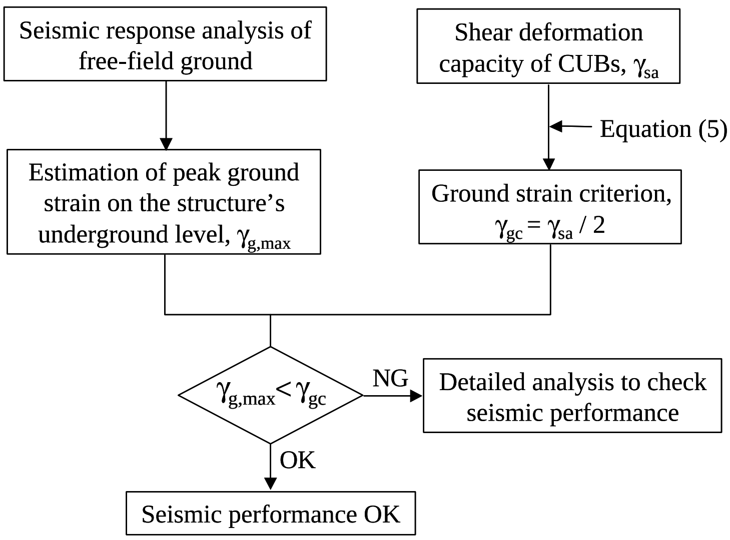


Figure 10. Flow diagram of the simplified evaluation method of the seismic performance of the CUBs

Since only the shear deformation of both ground and structure are considered herein, the equilibrium of one-dimensional shear stress in Figure 8 is applied to Equation (3). The equilibrium is given by

$$G_s \cdot g_s = G_g \cdot (g_g - g_s) + G_g \cdot g_g \tag{4}$$

where G_s = equivalent shear stiffness of the whole structure, γ_s = shear deformation (shear strain) of the whole structure, $G_s\gamma_s$ = structure shear stress, G_g = ground shear stiffness, γ_g = ground shear strain on the structure's underground level, $G_g(\gamma_g-\gamma_s)$ = ground shear stress due to the relative shear strain between free-field ground and the structure, $G_g\gamma_g$ = free-field ground shear stress on the structure's underground level. The first term of the right side of Equation (3), the inertia force acting on the structure is ignored, because the effect of the inertia interaction is very small.

The structure-ground shear strain ratio γ_s/γ_g is expressed as

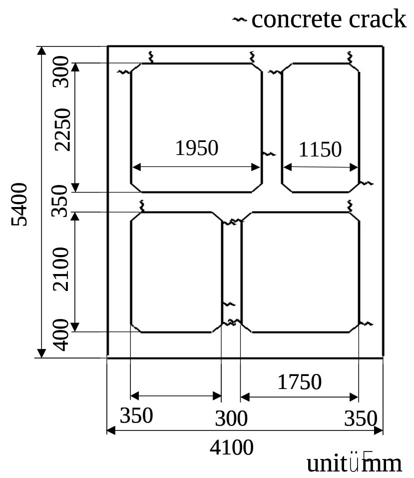


Figure 11. Cross section of the CUB at Kobe

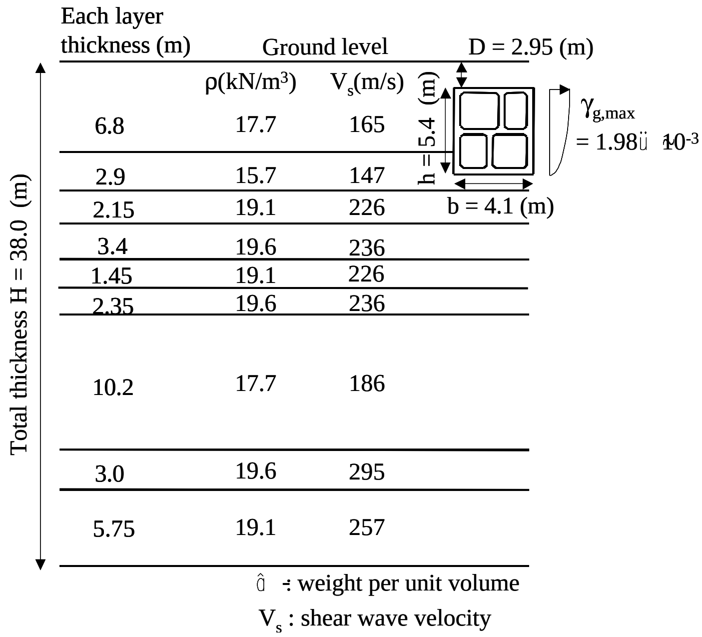


Figure12. Ground conditions at the site

$$\gamma_s / \gamma_g = (2G_g / G_s)/(G_g / G_s + 1) \tag{5}$$

Figure 9 shows the comparison between Equation (5) and the data of γ_s/γ_g, which are obtained by FEM analysis for the CUBs with standard rectangular cross sections. It is found that Equation (5) estimates the analyzed data of γ_s/γ_g well.

In equation (5), γ_s/γ_g approaches 2 as G_g/G_s gets large, which means the upper limit of γ_s/γ_g is 2. Therefore, even if the strong ground motion deforms the underground structures into the plastic range, γ_s does not exceed twice as large as γ_g. Additionally, it is explicable that the surrounding soil retains the underground structures ultimately, if the structures have enough ductility. From the upper limit of γ_s/γ_g, the ground strain criterion γ_{gc} is proposed as half of the shear deformation capacity γ_{sa}. The seismic performance of CUBs can be simply evaluated by using γ_{gc}. If the peak ground strain on the structure's underground level $\gamma_{g,max}$ calculated by the seismic response analysis of free-field ground is less than γ_{gc}, the response shear deformation γ_s does not exceed γ_{sa}. Figure 10 shows the flow diagram of the simplified evaluation method of the seismic performance of the CUBs.

3.2 **Practical example**

A practical example of the simplified evaluation method is demonstrated as follows. Figure 11 shows the CUB located at Kobe, which suffered small concrete crack damage from the 1995 Hyogoken-nanbu earthquake. Traces of concrete crack obtained by the inside inspection are drawn in Figure 11. Figure 12 indicates the multi-layered ground conditions at the site of the CUB.

The one-dimensional seismic response analysis (SHAKE) is conducted for free-field ground at the site. The ground motion observed at underground (G.L.-83m) near the site is used as the input wave for SHAKE. $\gamma_{g,max} = 1.98*10^{-3}$ is obtained by SHAKE.

The thickness of the structural members of the CUB is 300~400mm. The CUB has D13, D16 reinforcements of which diameters are 13, 16mm, respectively. In Table 2, the 2 floors type and d=350mm are applicable to the CUB. According to Table 2, γ_{sa} of the CUB is estimated to be 0.007. For the purpose of comparison, the push-over analysis of the CUB is also conducted. The relationship between γ_s and P/b is shown in Figure 13. According to the push-over analysis, γ_{su1} is 0.014. Table 3

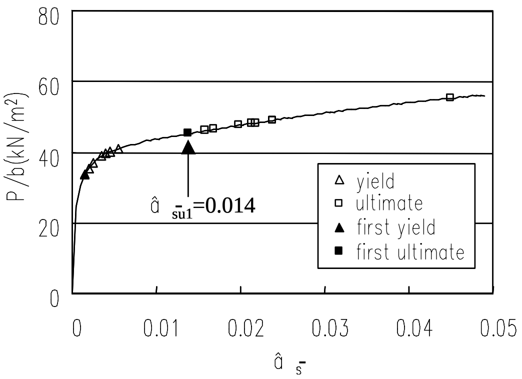


Figure 13. Relationship between γ_s and P/b

Table 3. Summary of the evaluation

$\gamma_{g,max}$	1.98×10^{-3}	
γ_{sa}	7.0×10^{-3} (Table 2)	$\gamma_{su1} = 1.4\times 10^{-2}$ (Push-over analysis)
γ_{gc}	3.5×10^{-3}	7.0×10^{-3}
$\gamma_{g,max} < \gamma_{gc}$ (OK)		
γ_s	1.37×10^{-3} (FEM analysis)	

shows the summary of the evaluation. γ_{sa} from Table 2 is half of γ_{su1} from the push-over analysis. Although γ_{sa} is conservatively estimated, the results of the evaluation are consistent. The response shear deformation γ_s computed precisely by FEM analysis is about 10% of γ_{su1}, which can explain the minor damage suffered from the Hyogoken-nanbu earthquake.

4 CONCLUSION

A simplified evaluation method for the seismic performance of CUBs with rectangular cross section is proposed in this paper. The scheme of the evaluation method is shown in Figure 10. The seismic performance of CUBs can be simply checked by the difference between the peak ground strain on the underground structure's level and the ground strain criterion based on the shear strain transmitting characteristics between ground and structure. Finally, the proposed method is applied to the CUB at Kobe that suffered minor damage from the 1995 Hyogoken-nanbu earthquake. The results indicate the CUB has enough seismic performance, which agrees well with the actual damage.

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