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Structure damage estimation due to tunnel excavation based on indoor model test

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Abstract. Population concentration in urban areas has led traffic management a central issue. To mitigate traffic congestions, the government has planned to construct large-cross-section tunnels deep underground. This study focuses on estimating the damage caused to frame structures owing to tunnel excavation. When constructing a tunnel network deep underground, it is necessary to divide the main tunnel and connect the divergence tunnel to the ground surface. Ground settlement is caused by excavation of the adjacent divergence tunnel. Therefore, predicting ground settlement using diverse variables is necessary before performing damage estimation. We used the volume loss and cover–tunnel diameter ratio as the variables in this study. Applying the ground settlement values to the settlement induction device, we measured the extent of damage to frame structures due to displacement at specific points. The vertical and horizontal displacements that occur at these points were measured using pre-attached LVDT (Linear variable differential transformer), and the lateral strain and angular distortion were calculated using these displacements. The lateral strain and angular distortion are key parameters for structural damage estimation. A damage assessment chart comprises the "Negligible", "Very Slight Damage", "Slight Damage", "Moderate to Severe Damage", and "Severe to Very Severe Damage" categories was developed. This table was applied to steel frame and concrete frame structures for comparison.

Keywords: indoor model test; settlement trough; forced displacement; frame structure; damage estimation chart

1. Introduction

Due to an increase in urban population, traffic has become a big issue in mega cities of the world. In South Korea capital (Seoul), there are many expressways around the city, which provide starting points for highways leading to the provinces. However, concentration of population in the city is very high. So, heavy traffic on all roads during commuting hours and weekends has resulted in severe congestion.

Building a large-cross-section tunnel beneath the existing road is one solution to solve this problem, so that traffic concentration could be divided. The tunnel could be connected with the main expressway via the convergence tunnel as shown in Fig. 1. The main tunnel will be constructed near the existing surface and other underground structures; in this situation, ground subsidence can be caused by tunnel excavation. These subsidence affects nearby structures. It is essential to estimate structural damage caused by tunnel excavation.

Before identifying damage to a building, the first thing should be to calculate the amount of settlement caused by

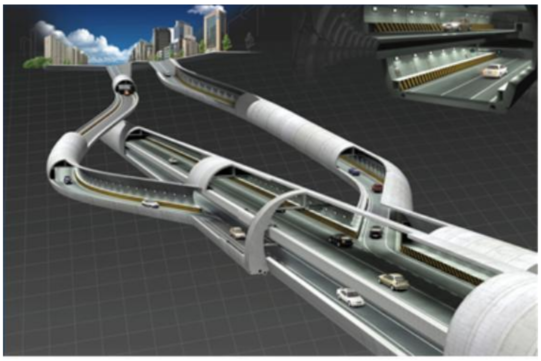

Fig. 1 Concept of large-cross-section tunnel in urban area

tunnel excavation (Marshall 2009). The settlement trough shape due to tunneling generally matches the Gaussian curve as shown in Fig. 2. The volume loss (ground loss) can be expressed as the ratio of Vs (Volume loss of surface settlement) to the notational excavated volume of the tunnel (Kim *et al.* 2018).

Clarke and Laefer (2014) have demonstrated the application of a new methodology that considers both physical and cultural aspects through the incorporation of building vulnerability criteria, consisting of the structure's status within the community and its current physical condition. This methodology offers a holistic approach to risk assessment through the culmination of damage and vulnerability predictions, facilitating the efficient use of project resources by targeting the appropriate at-risk

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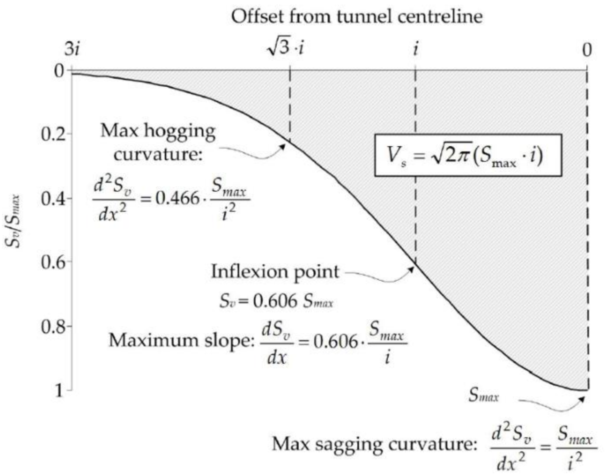


Fig. 2 Settlement trough expressed by Gaussian curve in which i: inflection point, S_{max}: the maximum settlement, S_v: vertical settlement and V_s: volume of surface settlement (Marshall 2009)

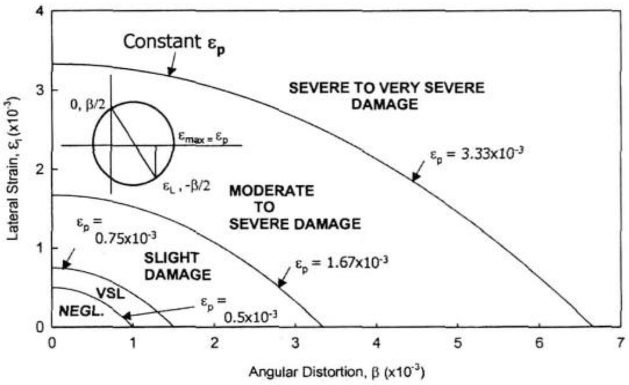


Fig. 3 Criteria for Prediction of Structural Damage (Son and Cording 2005)

buildings to prevent negative consequences arising from urban tunneling.

Assessment of building damage can also be made using damage chart designed as shown in Fig. 3. The maximum principal deformation ratio in a structure is obtained by a combination of angular and horizontal deformation in a structure using the state of strain theory, and the direction of the crack in the structure, which are orthogonal to each other (Son and Cording 2005).

In previous studies, damage assessment of adjacent structures due to tunnel excavation was rarely performed using indoor model tests. Most of them used numerical analysis to assess damage to the structure, and there were indoor centrifugal model tests to express tunnel excavation and building simultaneously. In this research, the indoor model test was carried out by calculating the settlement due to tunnel excavation in advance using an empirical formula and applying the calculated values to the structure.

2. Indoor model test set-up

2.1 Frame structures

Laefer *et al.* (2009) performed one-tenth scale laboratory test investigating the response of RC (Reinforced Concrete) frames to adjacent excavation induced settlement and was combined with numerical modeling to determine the most appropriate set of input parameters.

Son and Park (2012) analyzed the behavior of frame structures affected by ground displacement caused by tunnel excavation by numerical analysis according to construction conditions (ground loss) and characteristics of structure.

Chen *et al.* (2014), by using three-dimensional software, considered the interactions among structures-soil-tunnel system and the working condition of shallow-buried underground excavation is simulated in the foundation of frame structures with the short-pile.

The steel frame structure applied in this study was assembled by coupling 50 mm x 50 mm square pipes with a SPSR400 specification, according to KS D 3568. A similitude ratio of 1/20 was applied to the actual structure (18 m long and 12 m high), and the total length of the structure subject to the indoor model test was 900 mm long and 600 mm high. Further, structures of the same size were made from pipes welded to each other and a concrete structure of the same strength as shown in Fig. 4.

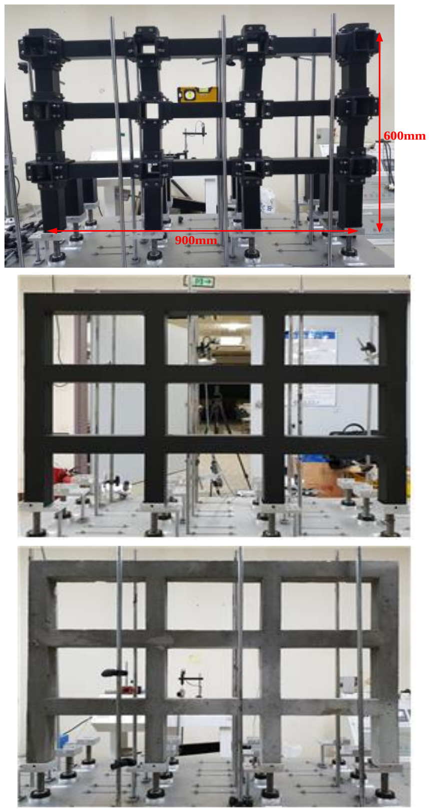
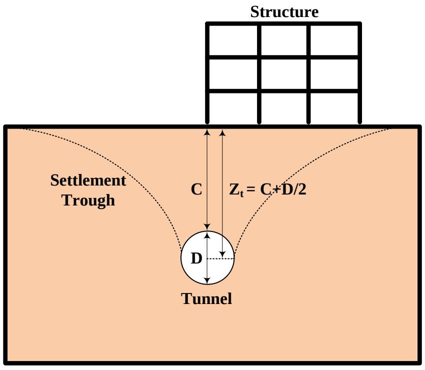
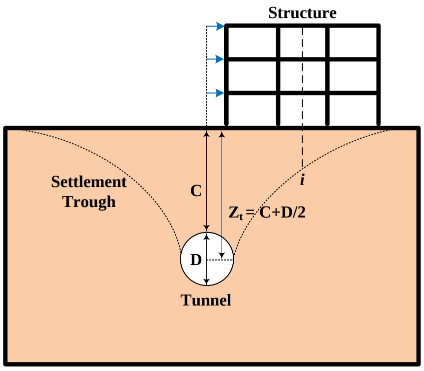


Fig. 4 Testing frame structures (assembled, welded, concrete)

The variables tested in the study are cover (C), eccentric distance (e), and volume loss (V_L) as shown in Fig. 5. Cover was divided into two cases based on severity conditions—40 m and 30 m. It was divided into two other cases in which eccentric distance is specified separately—one (e=0 condition), where a tunnel is located on the left side of the structure as shown in Fig. 5(a), and two (e=i



(a) The center of the tunnel matches the left side of the structure



(b) Center point of structure matches the inflection point of gaussian curve

Fig. 5 Concept of performed indoor model test

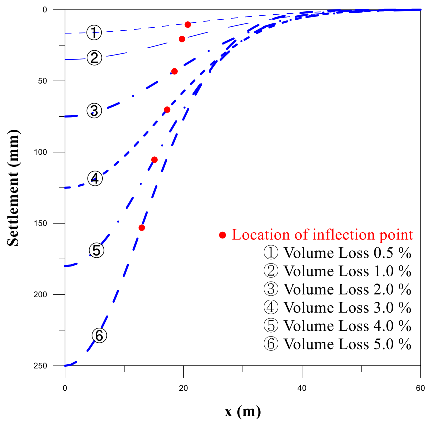
Table 1 Variables used in indoor model test for three frame structures and two eccentric locations

Case	Cover (C)	Volume loss (V_L)
T1	40 m	0.5%
T2		1.0%
T3		2.0%
T4		3.0%
T5		4.0%
T6		5.0%
T7	30 m	0.5%
T8		1.0%
T9		2.0%
T10		3.0%
T11		4.0%
T12		5.0%

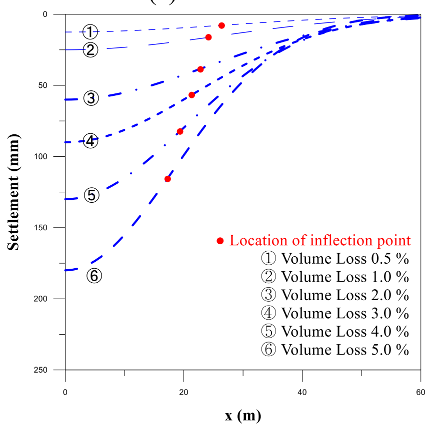
condition), when the center of the structure and the inflection point (i) of the gaussian curve match (Fig. 5(b)). The reason for matching the center of the structure with the inflection point was that the pre– and post– surface subsidence was different based on the inflection point and the impact on the ground structure would be significant, so the model test was conducted by matching the center of the structure with the inflection point. The volume loss was classified into six cases, from 0.5% to 5.0% as described in Table 1.

2.2 Settlement settings

Settlements are calculated with two (30 m and 40 m) cover depth and volume loss conditions as shown in Fig. 6. The value of maximum subsidence was adjusted to derive a subsidence close to the target volume loss and the forced displacement value. The following equations were used in the calculation (Chakeri *et al.* 2013, Zhang *et al.* 2014, Kim *et al.* 2018), and details are listed in Table 2.



(a) C = 30 m



(b) C = 40 m

Fig. 6 Gaussian curve used in model test

Table 2 Applied forced displacement according to variables

	Target V_L (%)	K	i (m)	S_{max} (mm)	Calculated V_L (%)	Applied S_{max} (mm)
C = 40 m	0.5	0.57	27.012	12.5	0.520	0.63
	1.0	0.55	26.044	25.0	1.002	1.25
	2.0	0.51	24.108	60.0	2.226	3.00
	3.0	0.47	22.174	90.0	3.071	4.50
	4.0	0.43	20.238	130.0	4.050	6.50
	5.0	0.39	18.303	180.0	5.071	9.00
C = 30 m	0.5	0.53	19.868	16.5	0.505	0.83
	1.0	0.51	19.105	35.0	1.029	1.75
	2.0	0.47	17.580	75.0	2.029	3.75
	3.0	0.43	16.055	125.0	3.089	6.25
	4.0	0.39	14.530	180.0	4.025	9.00
	5.0	0.35	13.005	250.0	5.003	12.5

$$Z_t = \mathrm{C} + \mathrm{D}/2 \quad (1)$$

$$K = 0.44 + (0.055 \times \mathrm{C/D}) - (0.041 \times \text{Target } V_L) \quad (2)$$

$$i = Z_t \times K \quad (3)$$

$$V_s = \sqrt{2\pi}(S_{max} \times i) \quad (4)$$

$$Calculated \quad V_L = (V_s/\mathrm{A}) \times 100 \quad (5)$$

D: Diameter of the tunnel (D = 14.4 m)
Z_t: The length from the surface to the center of tunnel
K: Coefficient of lateral pressure
V_L: Volume loss (=ground loss)
A: Area of the tunnel

The reason that target V_L is different from calculated V_L is the equation steps. The C, D, and Z_t values are given and to get calculated V_L, S_{max} needs to be adjusted to match target V_L. Therefore, this value is applied as an approximation, and errors occur in target and calculated V_L during this process.

2.3 Device of indoor model test

2.3.1 Settlement induction device

The settlement induction device system consists of a screw jack, a motor, 12 axes, a set of decelerators and a control box to control them as shown in Fig. 7. The specifications of the motor enable it to be driven at a speed of 20 mm/min (0.3333 mm/sec) by applying a deceleration ratio of 90. The control box allows the motor speed for each axis to be driven individually, giving enough control over the different forced displacements applied to the structure during the model test. In addition, magnetic bases were installed up and down so that vertical and horizontal displacements gauges could be attached after the construction and installation of the structure (Kim *et al.* 2005).

2.3.2 Displacement measuring device

The values shown in the damage chart (Fig. 3) are lateral strain (ε_L) and the angular distortion (β). Both values can be calculated from the horizontal and vertical displacement of the structure's point. Thus, the instrumentation required for the model test was a displacement gauge that could measure displacement, and a data logger that could read its value. In the case of the displacement meter, the maximum load carrying capacity (S_{max}) was 40 mm, so a product capable of measuring up to 50 mm was required. The data logger is connected to the computer and the displacements are measured by means of a separate program (Multi-scan). Even during the experiment, displacement patterns can be visually verified through graphs or values.

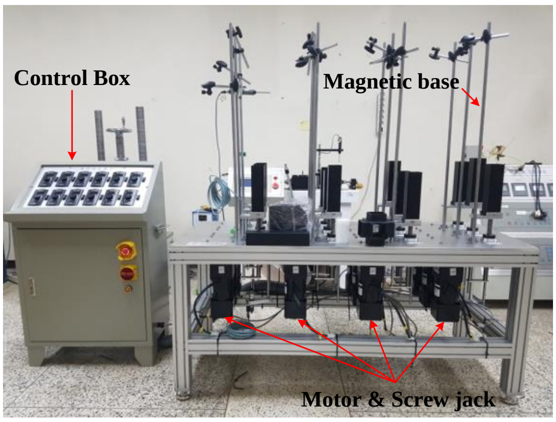


Fig. 7 Settlement induction device and control box

3. Indoor model test results

3.1 Cover 40 m condition

3.1.1 Assembled steel frame structure

In the e = 0 condition, it was found that there was negligible (NEGL) damage to the structure due to tunnel excavation, based on a volume loss of 1.002% at 40 m cover. However, the structure was placed within the 'Slight damage (SL)' range in the damage chart up to 3.071%, with the volume loss exceeding 1.002%. As the volume loss further increased, all the bays were in the 'Moderate to severe damage (MO to SV)' range in the damage chart from 4.0%, and when volume loss exceeded 5.071%, all bays were 'Severe to very severe damage (SV to VSV)' (Fig. 8(a)).

In the e = *i* condition, based on the inflection point, hogging and sagging occurred, causing further damage to the structure. The volume loss rate of 1.002% was in the 'Very slight damage (VSL)' area and, as in the previous case, the volume loss 3.071% was found to be located in the 'Moderate to severe damage' area. At the volume loss 4.0% and 5.0%, all bay was placed in the 'Severe to very severe damage' and, unlike in the previous case, the presence of structures at the inflection point location was found to cause more damage to the structure (Fig. 8(b))

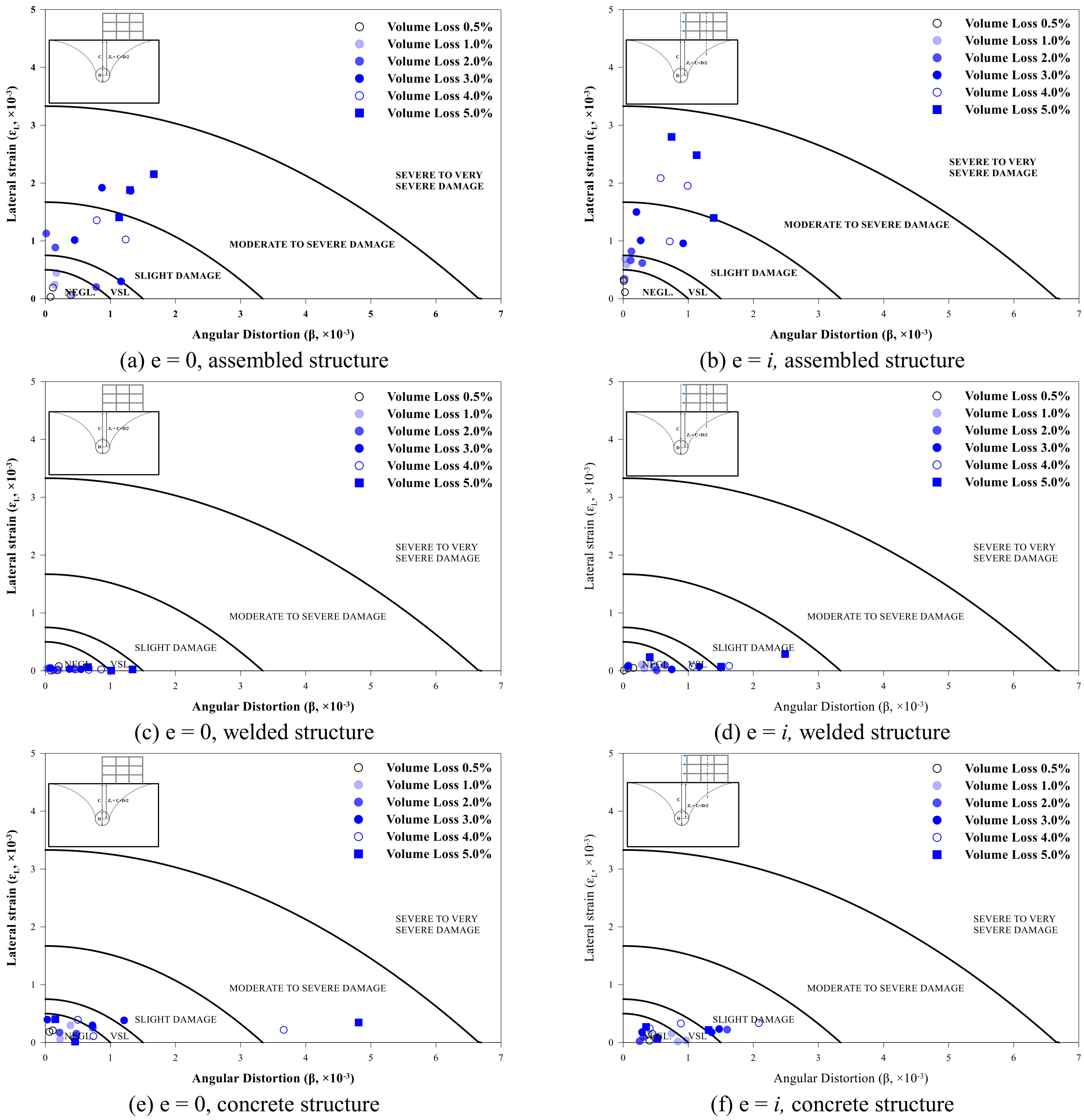
3.1.2 Welded frame structure

In the e = 0 condition, damage to structures caused by subsidence, due to tunnel excavation, was extremely rare (Fig. 8(c)). It was found that 3.071% (S_{max} = 90 mm) volume loss was without damage to the structure. However, when volume loss exceeds 4.05% (S_{max} = 130 mm), 'VSL' occurs on the damage chart. In addition, although the lateral strain of the structure itself was smaller than 0.1, the angular distortion was shown to be greater as the volume loss increased, and 'Slight damage' to the structure was found when volume loss exceeded 5.071% (S_{max} = 180 mm).

In the e = *i* condition, it was found that the tunnel had a greater impact on the structure than when it was located on the left side of the structure. In previous cases, it was found that no structural damage occurred up to 4.05% (S_{max} = 130 mm, *i* = 20.238 m), but if the structure is located above the inflection point, it caused 'VSL' in the damage chart from 4.05% (S_{max} = 130 mm, *i* = 20.238 m) volume loss, and 'Slight damage' occurs at 5.071% (S_{max} = 180 mm, *i* = 18.303 m) volume loss (Fig. 8(d)).

3.1.3 Concrete frame structure

In the e = 0 condition, when the tunnel centerline



(a) e = 0, assembled structure

(b) e = *i*, assembled structure

(c) e = 0, welded structure

(d) e = *i*, welded structure

(e) e = 0, concrete structure

(f) e = *i*, concrete structure

Fig. 8 Frame structure damage assessment chart (cover 40 m)

matches the structure's left side, it has been shown that there is little damage to the structure due to subsidence. No structural damage occurred up to 2.226% (S_{max} = 60 mm) volume loss and 'VSL' occurred to the structure when volume loss exceeded 3.071% (S_{max} = 90 mm). If the volume loss exceeded 4.05% (S_{max} = 130 mm) then it was found to have 'Slight damage' to the structure, but it did not have much effect on each bay of the structure. However, the lateral strain was greater than in a welded structure with the same 40 m cover. The overall distribution on the damage chart is shown in Fig. 8(e) for tunnel centerline consistent with the left line of the structure.

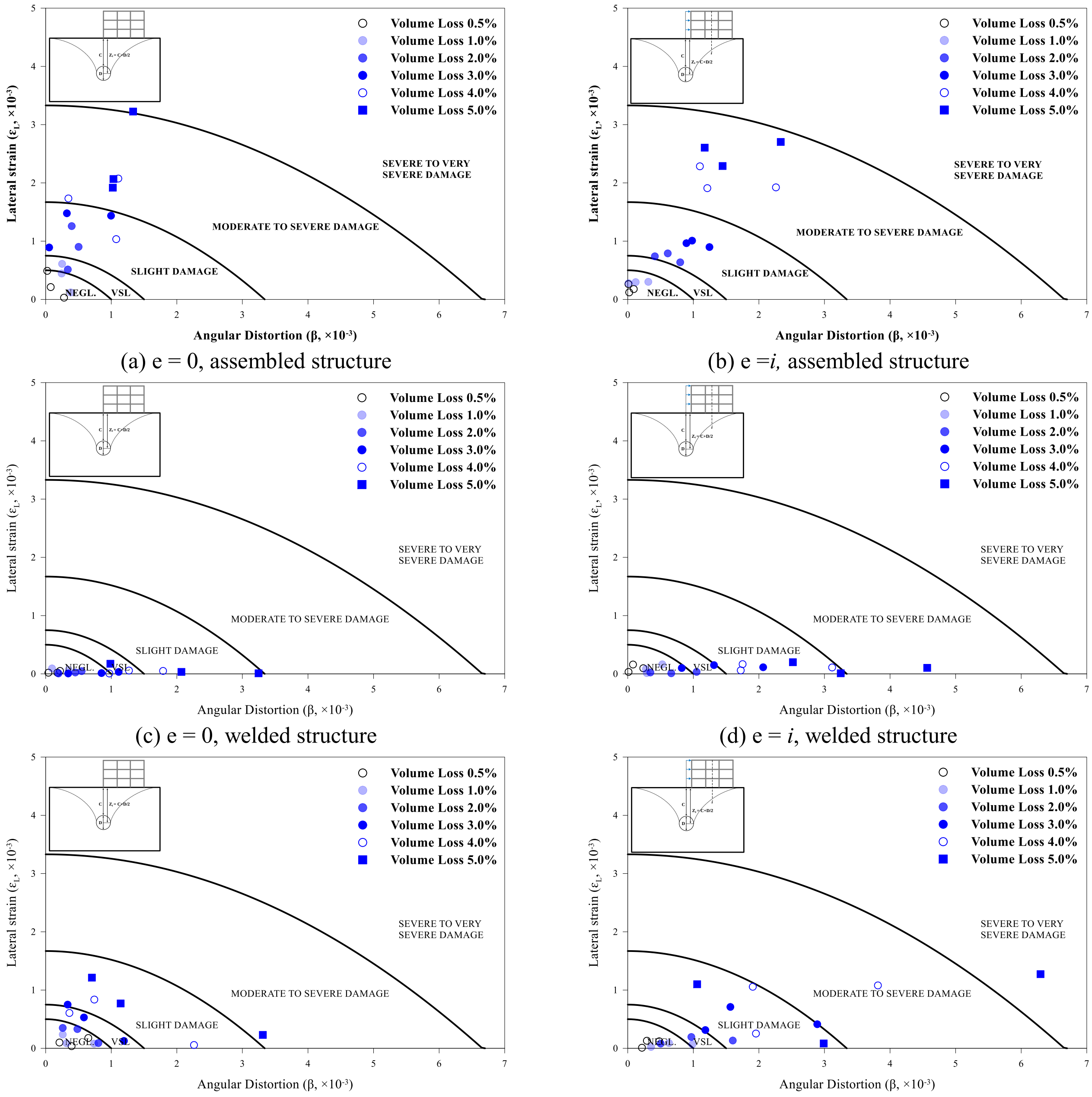
In the e = *i* condition, the volume loss was greater than 0.5%, and 'VSL' was caused to the structure at the time when the volume loss exceeded 2.226% (S_{max} = 60 mm, *i* = 24.108 m). In addition, if the volume loss is 3.071% (S_{max} = 90 mm, *i* = 22.174 m) it causes 'Slight damage' to the structure (Fig. 8(f)).

3.2 Cover 30 m condition

3.2.1 Assembled steel frame structure

In the e = 0 condition, subsidence of the ground, compared to the 40 m cover, increases both in lateral strain and angular distortion, causing greater damage to the structure. When the volume loss was 0.5%, more structural members were placed in the 'Slight damage' area, but from 1.0% volume loss and conditions of 40 m of cover, the extent of the increase in damage was approximately 1.12 times (Fig. 9(a)).

In the e = *i* condition, a volume loss of 3.0% under the



(a) e = 0, assembled structure (b) e = *i*, assembled structure

(c) e = 0, welded structure (d) e = *i*, welded structure

(e) e = 0, concrete structure (f) e = *i*, concrete structure

Fig. 9 Frame structure damage assessment chart (cover 30 m)

condition of 30 m of cover was located in the 'Slight damage' area, and it was found that when the volume loss was higher than 4.0%, it causing 'Moderate to severe damage' to the structure (Fig. 9(b)).

3.2.2 Welded frame structure

In the e = 0 condition, if the tunnel is located on the left side of the structure, it has been shown to have 'VSL' to the structure when volume loss exceeds 3.089% (S_{max} = 125 mm), unlike the condition of 40 m cover. The volume loss rate exceeded 4.025% (S_{max} = 180 mm), causing 'Slight damage' to the structure. As the volume loss reaches 5.003% (S_{max} = 250 mm), the structure was found to be 'Moderate to severe damage' (Fig. 9(c)).

In the e = *i* condition, it was found that the damage to the structure was greater than the 40 m cover conditions, and that the damage level of the structure was 'Slight damage' at 3.089% (S_{max} = 125 mm, *i* = 16.0549 m). Volume loss in excess of 4.025% (S_{max} = 180 mm, *i* = 14.5297 m) caused 'Moderate to severe damage' to the structure (Fig. 9(d)).

3.2.3 Concrete frame structure

In the e = 0 condition, concrete structures tend to have greater horizontal strain than welded structures. When the tunnel was located on the left-hand side of the structure, the damage level of the structure was greater, unlike in the 40 m cover condition. A volume loss of 2.029% (S_{max} = 75 mm) did not damage the structure as in the previous results, but when volume loss exceeded 3.089% (S_{max} = 125 mm), it was found to cause 'VSL' to the structure. At a volume loss of 4.025% (S_{max} = 180 mm), the structure received 'Slight damage' and in excess of that, volume loss of 5.003% (S_{max} = 250 mm) was found to have 'Moderate to severe damage' (Fig. 9€).

In the e = i condition, the lateral strain and angular distortion were greater than when the tunnel was located on the left-hand side of the structure and caused more damage to the structure compared to the same volume loss. The structure has already received 'Slight damage' at a time when the volume loss exceeds 3.089% (S_{max} = 125 mm, i = 16.0549 m) and is found to be located in the 'Moderate to severe damage' zone of damage in the range exceeding the volume loss 4.025% (S_{max} = 180 mm, i = 14.5297 m) (Fig. 9(f)).

4. Analysis summary

The results of structure damage assessment for the 72 number of cases are listed in Table 3. For the e = 0 condition, the welded structure shows better response from tunnel excavation than assembled and concrete structure. The comparison of the latter two cases (assembled and concrete structure) reveal that assembled structure shows almost similar results for 40 m cover except case T3. However, for 30 m cover, three cases (T8, T9, and T11) shows comparatively more damage for assembled structure than concrete. This higher damage values are due to the joint connections in the assembled structure.

For the e = i conditions, welded and concrete structures have similar damage response due to tunnel excavation for 40 m cover. However, for 30 m cover, the response of welded structure is better than concrete structure. Further, like e = 0 condition, in case of e = i condition the damage response is more in assembled structure than the other two.

Table 3 Experimental results comparison for the structure damage analysis

Case	e = 0			e = i		
	Assembled	Welded	Concrete	Assembled	Welded	Concrete
T1	NEGL	NEGL	NEGL	NEGL	NEGL	NEGL
T2	NEGL	NEGL	NEGL	VSL	NEGL	NEGL
T3	SL	NEGL	NEGL	VSL	NEGL	NEGL
T4	SL	NEGL	SL	SL	VSL	VSL
T5	MO to SV	NEGL	MO to SV	MO to SV	SL	SL
T6	MO to SV	VSL	MO to SV	MO to SV	SL	SL
T7	NEGL	NEGL	NEGL	NEGL	NEGL	NEGL
T8	VSL	NEGL	NEGL	NEGL	NEGL	NEGL
T9	SL	NEGL	NEGL	SL	VSL	VSL
T10	SL	VSL	SL	SL	VSL	SL
T11	MO to SV	SL	SL	MO to SV	SL	MO to SV
T12	MO to SV	SL	MO to SV	MO to SV	MO to SV	SV to VSV

Negligible: NEGL; Very Slight Damage: VSL; Slight Damage: SL; Moderate to Severe Damage: MO to SV; Severe to Very Severe Damage: SV to VSV

5. Conclusions

In this study, the damage assessment was performed by applying pre-calculated settlement through the theoretical equations to the structure using a settlement-induction-device.

Assembled and welded structures were found to have less structural damage under all conditions when compared to concrete structures. In the 40 m cover condition, the structure was found to be slightly more damaged at the inflection point divided by sagging and hogging, resulting in little or no damage to the structure up to 2.0% of the volume loss. For volume loss exceeding 3.0%, the displacement was found to be small but damaging the structure, regardless of its location. Overall, when the cover was 30 m, the surface settlement relative to the same volume loss increased by an average of 72%, showing a tendency to damage for conditions below the 40 m cover.

Also, there are three types of structures applied in this study, but these are not the real building around our circumstance. Thus, in future studies, the following points should also be considered:

(a) It is necessary to apply the groundwater depression in settlement calculation.

(b) It is necessary to apply the different types of structures (such as masonry) rather than a frame for real shape of building.

(c) To verify indoor model test, comparing the results with a numerical analysis.

(d) Both the indoor model test and the numerical analysis should be performed in 3-dimensions, which means having to consider the longitudinal direction due to tunneling.

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