Buildup of Soil Deformations and Damage to Subway Tunnels*

by

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1. INTRODUCTION

The intense ground motion of the Great Hanshin-Awaji Earthquake of 1995 caused a variety of damage to underground structures, such as deep foundations and tunnels. The remaining plastic deformations of cracked piles might have been largely due to inertia forces of their superstructures. However, even totally buried underground structures suffered serious damage. Daikai subway station of the Kobe Rapid Transit line, for example, was completely destroyed in this earthquake (Iida, et al., 1996). Many RC columns supporting the ceiling slab of the box tunnel were totally crumbled down (**Figure 1**); that failure was followed by a couple of meters subsidence of its overburden soil over the entire 90 m extent of the crushed subway station (**Figure 2**). Diagonal cracks remaining on all transverse walls of this station are suggestive that the tunnel box was alternately sheared in its transverse direction, and they are all important pieces of evidence proving the fact that underground structures were forcibly deformed by their surrounding soils. It is thus of great importance to discuss a possible correlation between the extents of soil deformations and the spatial variation of damage to tunnels.

Tanaka (1995) measured the displacements remaining on the ground surface in Kobe by comparing aerial photographs taken before and after the earthquake. His study stirs up curiosities for the possible causes of the remaining soil displacements. One possible interpretation is that the displacements are faint projection on the ground surface of the fault dislocations. Konagai et al. (1998a and 1998b), however, showed that some shallow sandy soils were subjected to quite large strains, far above a few percent, the fact evidenced by the observed dislocations of manhole rings. This paper describes the distributions of the remaining soil displacements along subways in Kobe, and discusses the correlation between the soil deformations and the spatial variation of damage to tunnels.

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2. DAMAGE TO YAMATE LINE

General

Both the damaged and not damaged sections must be equally discussed in the course of this study in order for the damage to be objectively viewed. From this viewpoint, the Yamate line of the Kobe City Rapid Transit Bureau, with a thorough investigation report available, will be suited for this purpose. This line did not suffer such a crushing damage as that to Daikai station (**Figures 1** and **2**).

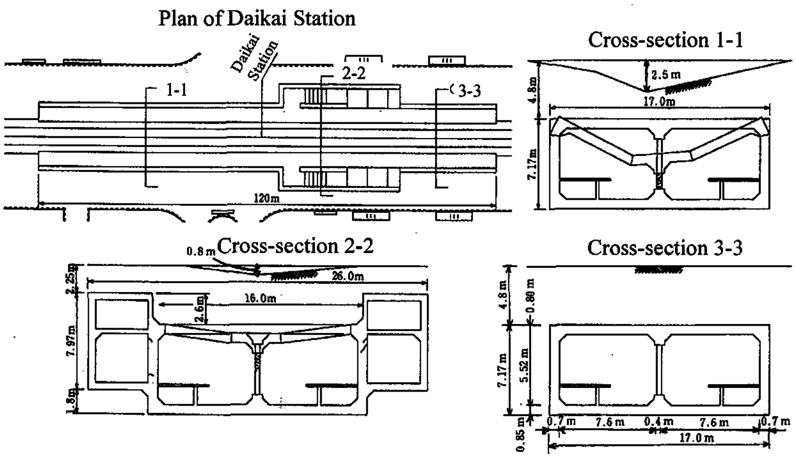


Figure 1. Damage to Daikai subway station of the Kobe Rapid Transit line

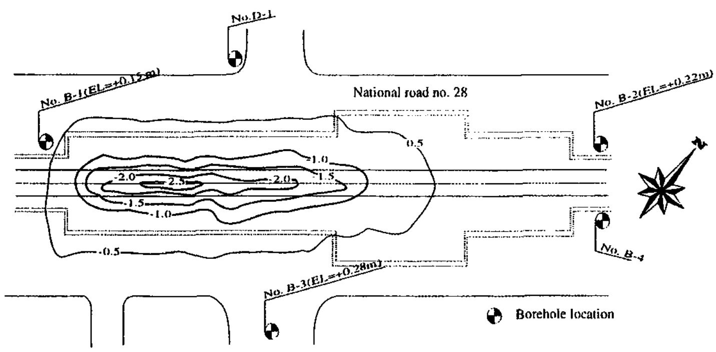


Figure 2. Contours of ground subsidence at Daikai station

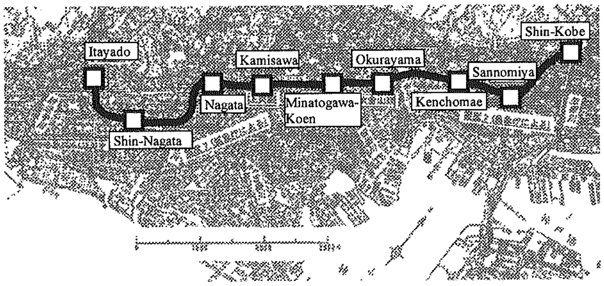
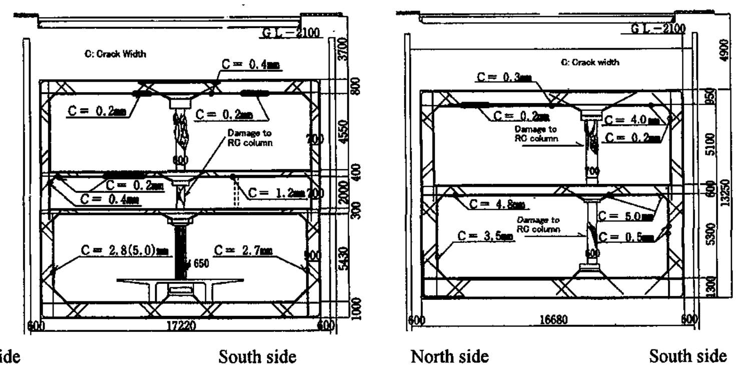


Figure 3. Yamate line of the Kobe City Rapid Transit Bureau

Walls and columns of this line, however, seem to bear clearer marks showing that the tunnel has experienced alternate shear in its transverse direction all the better for the fact that the cracked walls and columns remained barely standing there. This subway line, like the other railways in Kobe, goes from east to west through the long-spread city over narrow alluvial fans lined up along the Rokko mountains (**Figure 3**). The tunnel is box-shaped throughout the entire extent of the underground stretch from Itayado to Shin-Kobe. The west half of the line (Itayado—Okurayama) is double-tracked on the same level, whereas the east part for the two-level tracks extends from Okurayama to Sannomiya. Cracking of columns supporting the tunnel ceilings is a noticeable feature of the extensive structural damage to this tunnel. Seriously cracked columns were mostly found at three places, Shin-Nagata station and its eastern approach (about 400 m), Kamisawa station and its east and west approaches (about 720 m), and Sannomiya station (about 310 m). In these sections longitudinal cracks were found on walls, ceilings and floors. Transverse cracks were found over the entire extent of the line.

Cracked RC columns

Kamisawa station suffered the most serious damage on this line. **Figure 4(a)** shows a cross-section (G2) of this station, a three-story RC box with a platform located on the bottom. The roofs of the first and the second basements were supported by RC columns, whereas steel pipes sustained the roof of the bottom basement. The upper parts of the RC columns in the first basement were cracked on a slant causing concrete fragments to have come off, and eventually, exposed reinforcing bars were outwardly buckled. These shear cracks were all slanting down to the south causing the ceiling to subside a couple of centimeters. Shear cracks were also found on the columns of the second basement, but no serious deformation was found on the steel columns. **Figure 4(b)** shows the cross-section (C), 100 m west of the G2 cross-section, a two-level RC box divided out of the symmetric proportion with RC columns into sea-side (south) and mountain-side (north) ducts for the double tracks. These RC columns were also cracked seriously, and major cracks were mostly slanting down to the south, resulting in the subsidence of the ground surface exceeding 1 cm.



(a) Cross Section (G2)

(b) Cross Section (C)

Figure 4. Cross sections of Kamisawa station

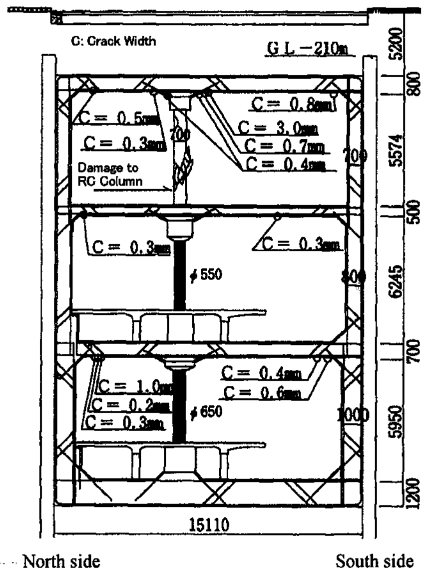


Figure 5 Cross section (I3) of Sannomiya station

Figure 5 shows a cross-section (I3) at Sannomiya station, a three-level box with the two-level platforms located on the second and the bottom basements. RC columns supporting the roof of the first basement were cracked, but the major cracks were on the slant down to the north, differing from those at Kamisawa and Shin-Nagata stations.

Displacements remaining on the ground surface

Tanaka (1995) measured the displacements remaining on the ground surface in Kobe by comparing aerial photographs taken before and after the earthquake. Exact positioning of reference points for triangulation was made by utilizing GPS (Global Positioning System), which procedure, with erratic readings on 1/500 scale maps included, may cause some 0.2 to 0.25 m errors in terms of standard deviation. **Figure 6** describes the distributions of the remaining soil displacement along the subway. It is noted here that solid circles in **Figure 6(b)** indicate a clear general northward movement of the ground, whereas the subway line through the long-spread city inevitably runs from north-east to south-west. Therefore, the general soil deformation can be resolved into two orthogonal components with respect to the subway line, the components in the north-east longitudinal and north-west transverse directions (**Figures 6(c)** and **6(d)**). **Figure 6(e)** shows vertical components of the ground surface displacements. The section between Itayado and Shin-Nagata seems to have heaved up by about 20—30 cm, whereas the Nagata—Kamisawa section has subsided to a similar extent. No clear general upheaval nor subsidence was seen in the section for the two-level tracks extending from Kenchomae to Sannomiya, and a sudden subsidence reaching 70 cm was found near Shin-Kobe station.

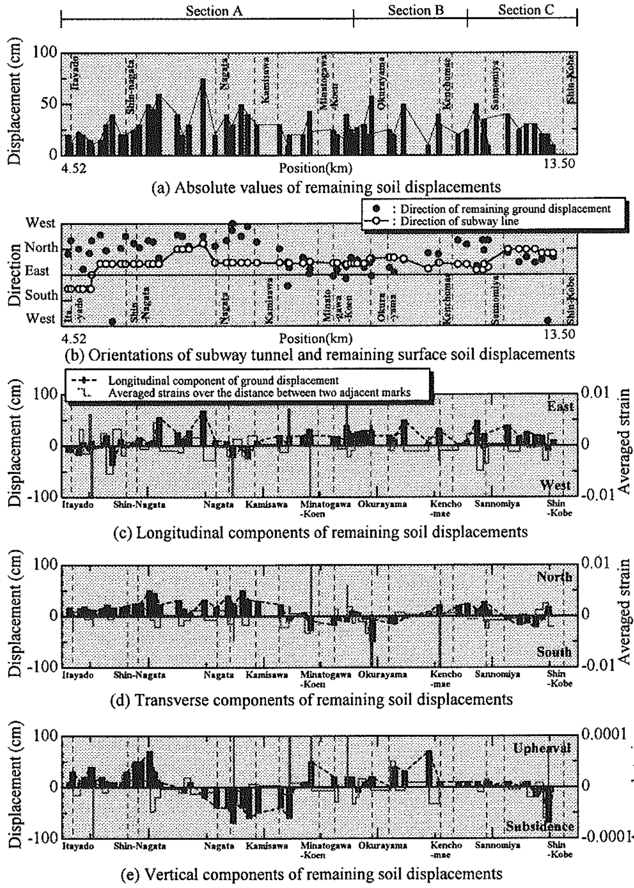
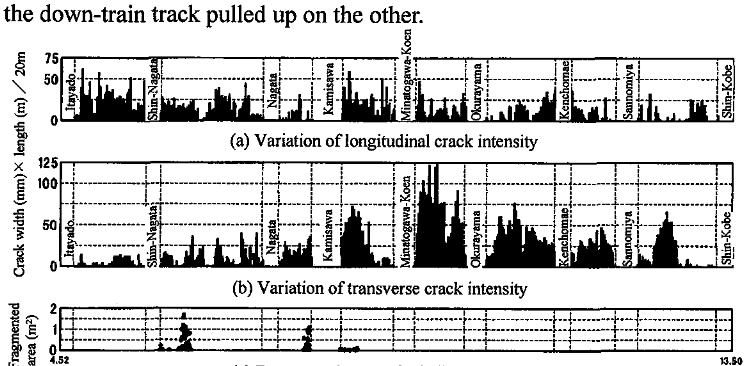


Figure 6 Distribution of remaining soil displacements along Yamanote subway line

In this paper, the extent of damage to the tunnel is described in terms of some indexes. Crack intensity is a cumulative product of a crack opening and its length over a 20 m longitudinal distance. The second index, "fragmented area", is the cumulative area of fragmented RC columns over the same distance of 20 m. Variations along the subway line of the transverse and longitudinal crack intensities and the fragmented area are shown in **Figures. 6(a)-6(c)**. Among them, sharp spiky rises of the "fragmented area" in **Figure 6(c)** clearly indicate the locations where the tunnel was most seriously damaged, and they seem to be consistent with the spatial distribution of transverse displacements remaining on the ground surfaces (**Figure 6(d)**). As has been mentioned, major cracks on RC columns slanted down to the south, the fact suggesting that these tunnel cross-sections followed alternate and forcible movements of the surrounding soils in the transverse directions, and the first intense southward shake in the earthquake caused the cracks on the south slant to be wide opened.

Transverse cracks, which were found over the entire extent of the subway line, are considered to have a close correlation with longitudinal strains induced within a tunnel. It is, however, noted that the cracks were mostly found on the roofs as shown in **Figures 7** and **8**; the fact may evidence that these tunnel sections were bent up as well. As for the longitudinal cracks, relatively many cracks were found at sections where the tunnel goes through clays and/or the sections for the two-level tracks with the down-train track pulled up on the other.

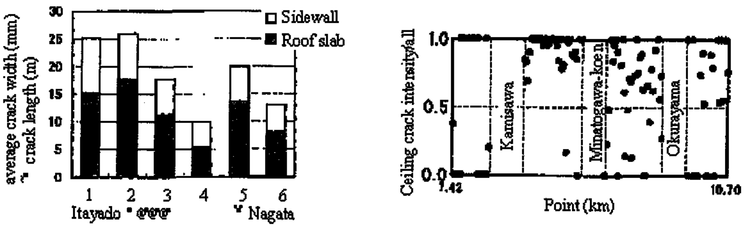


(a) Variation of longitudinal crack intensity

(b) Variation of transverse crack intensity

(c) Fragmented areas of middle columns

Figure 7. Damage to Yamate line



(a) Spatial distribution of cracks between Itayado and Nagata

(b) Variation of ceiling crack ratio with distance

Figure 8. Ratio of transverse ceiling cracks to all

3. CONCLUSIONS

This paper described the distributions of the remaining soil displacements along a subway, the Yamate line of the Kobe City Rapid Transit Bureau, and discussed the correlation between the soil deformations and the spatial variation of damage to the tunnel. The tunnel is box-shaped throughout the entire extent of the underground stretch from Itayado to Shin-Kobe. The west half of the line (Itayado—Okurayama) is double-tracked on the same level, whereas the east part for the two-level tracks extends from Okurayama to Sannomiya. Cracking of columns supporting the tunnel ceilings is a noticeable feature of the extensive structural damage to this tunnel. Seriously cracked columns were mostly found at three places, Shin-Nagata station and its eastern approach (about 400 m), Kamisawa station and its east and west approaches (about 720 m), and Sannomiya station (about 310 m). At these three points, the transverse component of a clear general northward displacement remaining on the ground surfaces seems to reach its peak values.

The field data provided in this chapter are certainly not sufficient yet for further detailed discussions, because only the surface soil displacements do not give any clear indication of possible shear stains of soil without deeper soil deformations. Konagai et al. (1998a and 1998b), however, showed that some shallow sandy soils were subjected to quite large strains, far above a few percent, the fact evidenced by the observed dislocations of manhole rings. Regarding these large deformations of soil, only a one-dimensional soil model, in which an infinite number of the completely same soil columns were virtually lined up side by side, would not provide a trustworthy result beyond the peak strength of the soil. The importance of studying possible extents of plastic deformations of soils experiencing this intense shake, thus, emerges from these findings and discussions through the investigations.

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