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SEISMIC BEHAVIOUR OF GEOSYNTHETIC—REINFORCED SOIL RETAINING WALLS

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ABSTRACT

For the last decade, geosynthetic-reinforced soil retaining walls with a full-height rigid facing that was cast-in-place by staged construction procedures were constructed in Japan to a total length exceeding 26 km as important permanent structures mainly for railways and partly for highways. All this type of geosynthetic-reinforced retaining walls located in the affected area of the 1995 Hyogo-ken Nanbu Earthquake performed very well, showing their very high seismic stability.

1. INTRODUCTION

A construction system for permanent geosynthetic-reinforced soil retaining walls (the GRS-RW system; Figure 1), is now widely used in Japan (Tatsuoka et al., 1997). This system can be characterized by the following features:

(a) The use of a full-height rigid (FHR) facing that is cast-in-place using staged construction procedures;

(b) The use of a polymer grid reinforcement for cohesionless soils to provide good interlock with the backfill soil, and the use of a composite of non-woven and woven geotextiles for nearly saturated cohesive soils to facilitate both drainage and tensile-reinforcement of the backfill;

(c) The use of relatively short reinforcement; and

(d) The use of low-quality on-site soil as the backfill, if necessary.

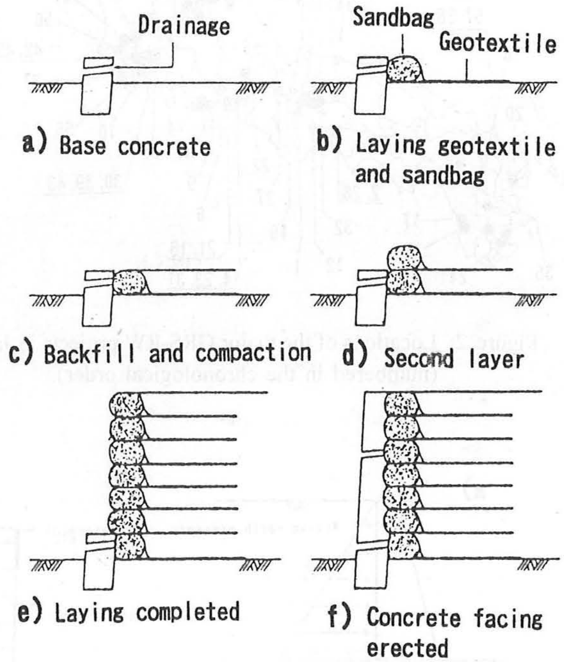

Figure 1: Standard staged construction procedures for a GRS-RW; a) concrete base; b) geotextile and gravel bags placement for the first layer; c) backfill and compaction; d) placement of the second layer of geotextile and gravel bags; e) all layers constructed; f) concrete facing constructed.

The staged construction method (Figure 1) consists of the following steps:

1) a small foundation for the facing is constructed;

2) a geosynthetic-reinforced soil wall with wrapped-around wall face is constructed with a help of gravel-filled bags placed at the shoulder of each soil layer; and

3) a thin and lightly steel-reinforced concrete facing is cast-in-place directly adjacent to the wall face after the deformation of the backfill and the subsoil layer beneath the wall has taken place, and a good connection is made between the facing and the main body of the wall.

A large number of permanent GRS-RWs with FHR facings, typically 5 m-high, to support important railway tracks and highways have been constructed to a total length exceeding 26 km as of April, 1997 (Figure 2). Reinforced soil retaining wall systems in general are cost-effective because the facing structure that is much simpler than that of most conventional retaining systems, which results into lower construction cost, higher construction speed and use of lighter construction machines. In addition, the wall performance is equivalent to, or even better than, that of the conventional type soil retaining systems. In addition, for flexible walls, the pile foundation that supports the facing of conventional retaining wall systems becomes unnecessary, resulting in a more cost-effective system.

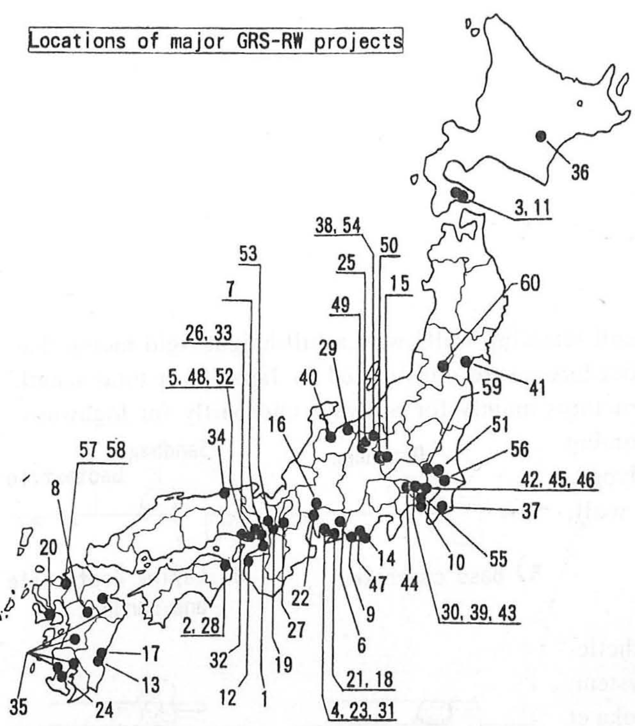

Figure 2: Locations of the major GRS-RW projects in Japan (numbered in the chronological order).

Using the design earth pressure, which is usually the active earth pressure in the unreinforced backfill, a conventional type retaining wall is designed as a cantilever structure supported at its base (Figure 3a). For this reason, large internal moment and shear force may be mobilized in the facing

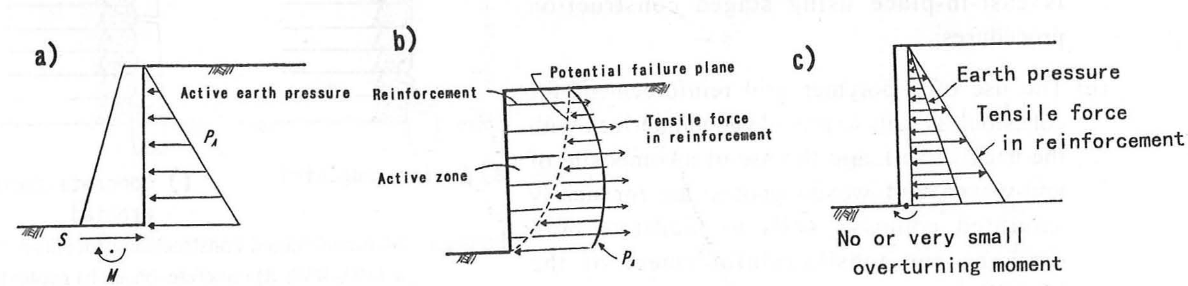

Figure 3: Force equilibrium for: a) a conventional type retaining wall; b) a reinforced soil retaining wall: c) a FHR facing of GRS-RW.

structure, and a large overturning moment and sliding force may develop at the bottom of the wall structure. In the case of a reinforced soil retaining wall, the backfill is retained by tensile force in the reinforcement (Figure 3b). The conventional explanation, which is misleading, is that because of this reinforcement effect, only very small earth pressure acts on the back of the facing, and accordingly only a very light and flexible facing is required to contain the backfill soil. Realistically, however, the earth pressure acting on the back of the facing can never approach zero unless the backfill soil is very cohesive, or unless a large amount of soil arching develops between two vertically adjacent reinforcement layers. If the earth pressure activated on the back of the facing is approximately zero, there must be zero tensile force at the connection between the reinforcement and the back of the facing, which results into a large reduction of the soil retaining capability of reinforcement (Tatsuoka, 1993). Consequently, as the lateral confining pressure on the soil in the active zone decreases, the active zone becomes more deformable and less stable, particularly when the backfill is a cohesionless soil.

The use of a FHR facing is more effective for increasing the wall stability and reducing the wall deformation than using a relatively flexible facing such as a discrete panel facing or a wrapped-around facing (Tatsuoka et al., 1989). Tatsuoka (1993) classified the different types of walls based on facing rigidity and discussed the contributions to wall stability. In the current design method for the GRS-RW system, a FHR facing is designed to support the earth pressure developed in an unreinforced backfill (Horii et al., 1994). However, the internal moment and the shear forces in the facing, the overturning moment, and the sliding force activated at the bottom of the facing can be very small because a FHR facing behaves as a continuous beam supported by a number of reinforcement layers with a very short vertical spacing (i.e., 30 cm) (Figure 3c). Therefore, the facing can be very thin and the required amount of steel-reinforcement in the facing is minimal. The minimum facing thickness specified for the GRS-RW system is 30 cm, which is based on constructability considerations. This thickness is typically larger than that based on structural requirements. In addition, a pile foundation used to support the facing is not necessary, mainly because the wall behaves a self-supported structure (Figure 3c).

It has been advocated that a geosynthetic-reinforced soil retaining wall with a flexible or deformable facing can accommodate the deformation of the backfill and the underlying subsoil layer. However, it is desirable that a retaining wall be rigid and stable. This contradiction can be resolved by the staged construction method and the use of a FHR facing (Figure 1), that is:

(a) Potential damage to the connections between the facing and the reinforcements due to settlement of the backfill relative to the rigid facing is avoided.

(b) Good compaction of the backfill adjacent to the back of the facing can be achieved by allowing relatively large outward lateral displacement to occur at the temporary wall face. Accordingly, sufficiently large tensile strains can be developed in the reinforcement.

(c) The major portion of the potential deformation of the backfill and the subsoil layer takes place before facing construction, and hence good alignment of the facing is possible. Particularly, the facing is free from the effects of vertical force caused by the downward force caused by the reinforcement layers that settle relative to the facing during and after the compaction of the backfill.

2. SEISMIC STABILITY OF WALL

2.1 General

At 5:46 a.m. on the 17th January 1995, a devastating earthquake measuring 7.2 on the Richter scale hit the southern part of Hyogo Prefecture, including Kobe City and neighbouring urban areas. In the severely affected areas (Figure 4), an extensive length of railway embankments had been

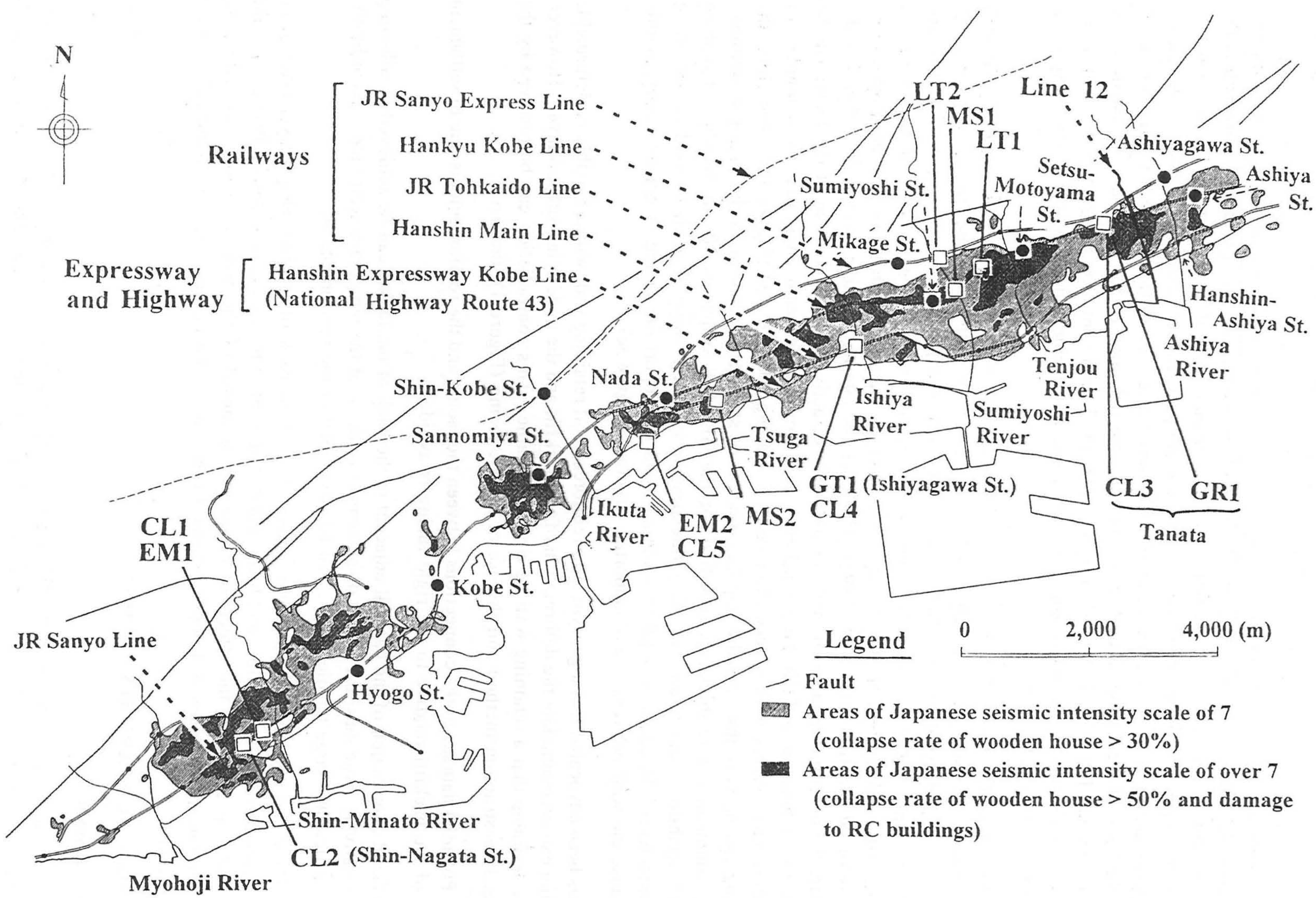

Figure 4: Seriously damaged areas during the 1995 Great Hanshin Earthquake; EM means damaged embankments.

constructed more than seventy years ago before the earthquake, which had a number of old and new retaining walls. Most of the walls were seriously damaged (Tatsuoka et al., 1996a, 1996b). The conventional types of retaining walls can be categorized into four groups:

(1) masonry retaining walls (denoted by MS in Figure 4);
(2) leaning-type (supported type) unreinforced concrete retaining walls (LT);
(3) gravity-type unreinforced concrete retaining walls (GT); and
(4) cantilever-type or inverted T-shaped type steel-reinforced concrete (RC) retaining walls (CT).

The first three types of retaining walls were most seriously damaged, while the damage to cantilever walls was generally less serious.

2.2 Tanata Wall

Despite the fact that the seismic intensity at the site was at the severest level, the damage to a GRS-RW with a FHR facing located at Tanata (GR1 in Figure 4) was significantly less serious when

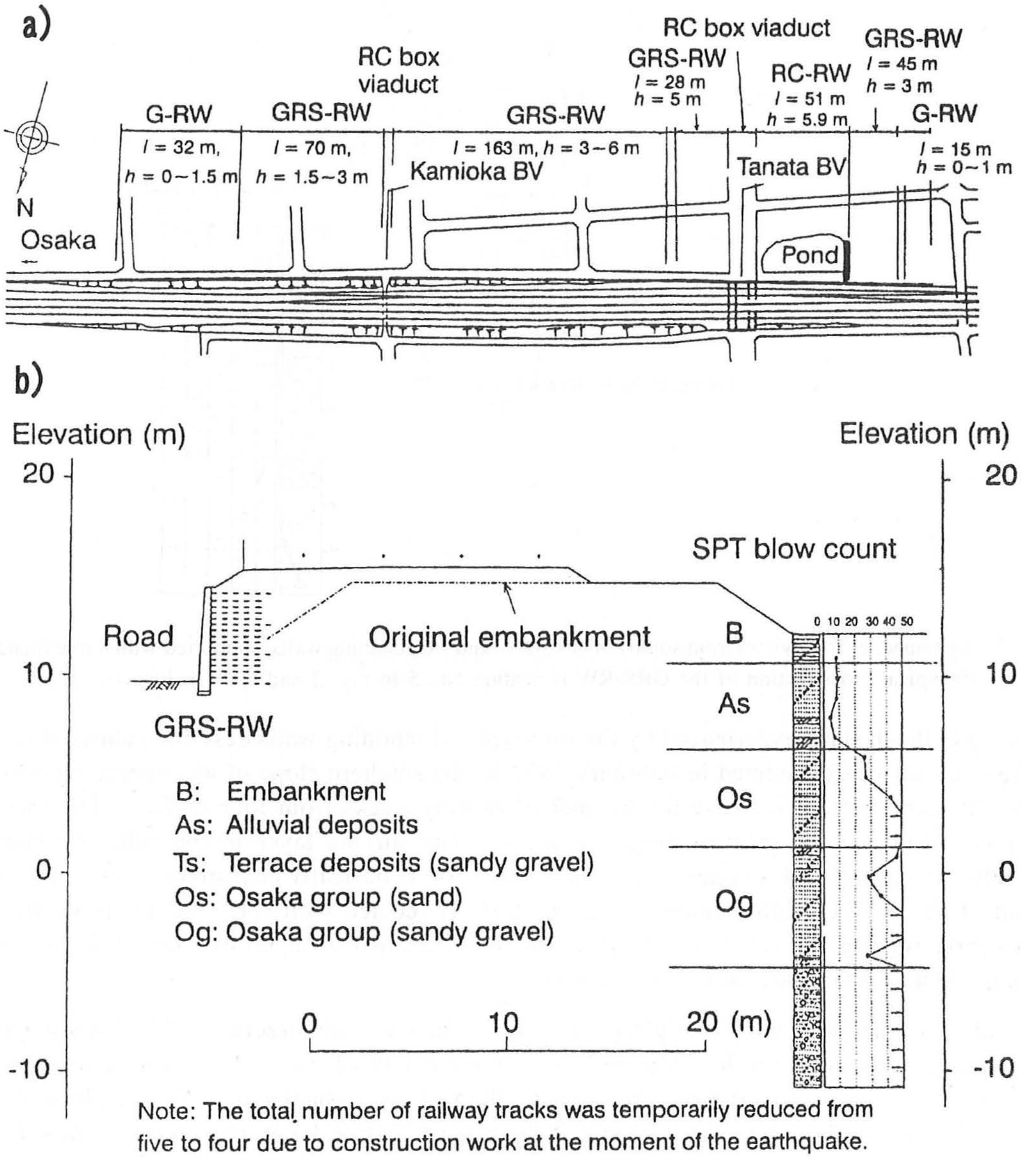

Figure 5: Tanata wall: a) plan view; b) cross-section of embankment

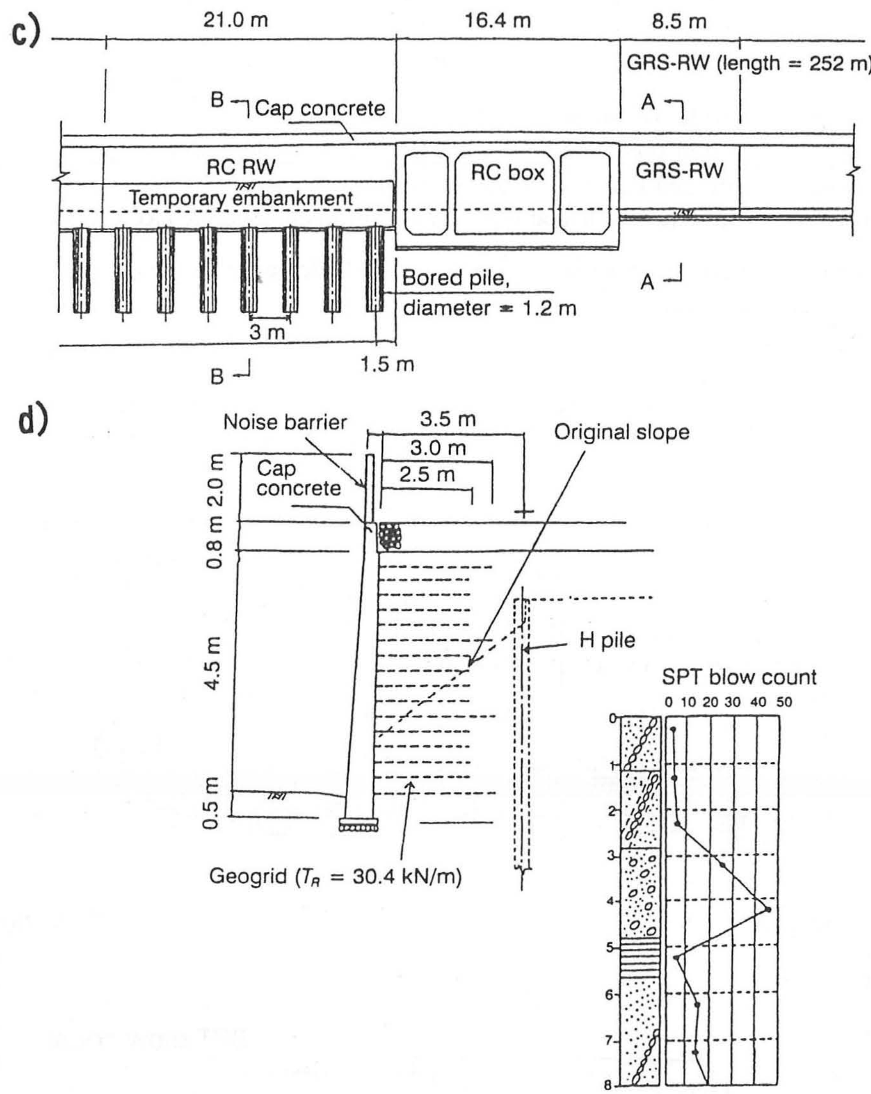

Figure 5: continued. c) front view (from south) of GRS-RW and RC retaining walls, supported with a pile foundation; d) typical cross-section of the GRS-RW (Location No. 5 in Fig. 2 and GR1 in Fig. 4).

compared to the damage experienced by the four types of retaining walls described above (Figure 5). The Tanata wall was completed in February 1992 on the southern slope of an existing embankment for the JR Kobe Line to increase the number of railway tracks from four to five. The total wall length is 305 m and the greatest height is 6.2 m. The surface layer in the subsoil consists of relatively stiff terrace soils (Figure 5b). The backfill soil is basically cohesionless soil with a small amount of fines. The reinforcement is a geogrid (PVA) coated with soft PVC for protection, and has a nearly rectangular cross-section of 2 mm by 1 mm and an aperture size of 20 mm with a nominal tensile rupture strength of 30.4 kN/m.

This wall deformed and moved slightly laterally in an outward direction. The largest outward displacement occurred at the location with the largest height of wall. This part of the wall is in contact with a RC box culvert structure crossing the railway embankment. The displacement was 26 cm and 10 cm at the top of the wall and at the ground surface level, respectively. Based on the following facts and despite these observations, the performance of the GRS-RW was considered satisfactory by the railway engineers responsible for this structure:

Figure 6: Side view of Tanata wall immediately after the earth-quake

(a) The peak ground acceleration at the site was estimated to be more than 700 gals (0.7 g). That is confirmed by the very high collapse rate of wooden houses at the site (Figure 6). Many of the collapsed ones were constructed less than about ten years ago.

(b) On the opposite side of the RC box structure, a RC retaining wall with the largest height of about 5.4 m (Figure 7) had been constructed concurrently with the GRS-RW. This wall is supported by a row of bored piles despite the similar subsoil conditions for the GRS-RW. Therefore, the construction cost per wall length of the RC retaining wall was approximately double to triple of that for the GRS-RW. In addition, a temporary cofferdam still existed at the time of the earthquake in front of the RC retaining wall. This may have contributed to the stability of the RC retaining wall during the earthquake. Despite these differences, the RC retaining wall displaced similarly to the GRS-RW; i.e., at the interface with the RC box structure, the outward lateral displacement of the RC Retaining wall was 21.5 cm at the top and 10 cm at ground level.

(c) The length of geogrid reinforcement used in GRS-RWs with FHR facings is generally shorter than that for most metal strip-reinforced soil retaining walls and other types of GRS retaining walls having deformable facings. For conservatism, most of the GRS-RWs with FHR facings constructed to date have several longer reinforcement layers at higher levels (Figure 7). For the Tanata wall, the length of all reinforcement layers were truncated to approximately the same length due to construction restraints at the site (Figure 5d). This arrangement may have reduced the seismic stability of the wall; the wall would have tilted less if the several top geogrid layers had been made longer.

2.3 Other GRS-RWs Having FHR Facings: In addition to the Tanata GRS-RW, the following GRS-RWs with FHR facings had been constructed at three other locations where the seismic intensity was five or six on the Japanese intensity scale and a number of wooden houses, railway and highway embankments and conventional retaining walls were seriously damaged. However, these GRS-RWs were not damaged at all (Tatsuoka et al., 1996b).

(a) Amagasaki No.1 wall (Figure 7) is the first large-scale construction project of the GRS-RW system to directly support the tracks of a very busy railway (Kobe). The average wall height is 5 m and the total length is 1,300 m. At a few locations along the wall, the foundations for steel frame structures for an electric power supply were constructed inside the reinforced zone. Four pairs of GRS bridge abutments were also constructed to directly support bridge girders.

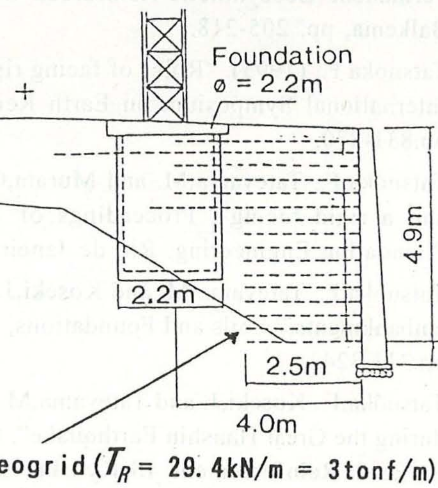

Figure 7: Typical cross-section of GRS-RWs for the Kobe Line at Amagasaki (Location No. 7 in Fig. 2).

(b) Walls having a maximum height of 6.3 m and a total length of 120 m at Maiko site in Tarumi-ku, Kobe City (Figure 4), were completed in May 1993 in order to expand the top of the road, adjacent to one of the approach roads to the Akashi Kaikyo (Strait) Bridge, which was under construction at the time of the earthquake. This site is located only 5 km from the epicenter.

(c) Amagasaki No.2 with a height of 3 to 8 m and a length of approximately 400 m, located west of the Amagasaki No.1 GRS-RW. The wall was completed in March 1994 to support a new approach fill for a JR bridge of the Fukuchiyama Line.

One of the mechanisms which make the GRS-RW with a FHR facing much more stable against seismic forces than conventional gravity-type retaining walls would is that the reinforced zone can behave as a relatively flexible monolith mass with a relatively large width/height ratio. For additional discussions with regard to the seismic stability of GRS-RW systems, refer to Tatsuoka et al. (1996b).

3. SUMMARY

The GRS-RW system reported in this paper has been used to construct important permanent retaining walls and bridge abutments for railways and highways. The authors believe that their use is due only to their cost-effectiveness, but also to that their performance is equivalent to, or even better than, that of other modern RC retaining walls and RC bridge abutments. A very good performance of the walls during the 1995 earthquake ensured the above. In fact, damaged conventional walls were reconstructed to GRS-RWs with FHR facings for a length more than 2 km. One of the prime reasons for the success of the GRS-RW system is the use of a proper type of geosynthetic (a geogrid for cohesionless soils or a nonwoven/woven geotextile composite for nearly saturated cohesive soils), and the use of a full-height rigid facing that are cast-in-place using staged construction procedures.

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