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Rapid restoration for a seriously damaged railway embankment during violent earthquakes

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ABSTRACT: The violent earthquakes that rocked Chuetsu district of Niigata Prefecture caused heavy damage. Especially, the embankment for a Niigata track (down line) of the Joetsu line suffered serious damage near the tunnel portal on the undercut slope (convex bank), which was built on the valley side formed by erosion from the Shinano River. The failed railway embankment would have to be restored and reinforced as early as possible to resume the railway service that plays a critical role in the region's mass transit. In order to reduce the volume of embankment, which would have a great impact on the construction period, the Reinforced Railroad/Road with Rigid facing (RRR) method was adopted, which had been applied to many railway embankment sites and would enable the construction in a narrow space without removing colluvium. This paper describes the phases of the embankment restoration from investigation to design and construction.

1 INTRODUCTION

At 17:56 on October 23, 2004, an earthquake with a moment magnitude of 6.8 occurred directly above its epicenter in Niigata Prefecture (Chuetsu district) located approximately 195 km north-northwest of Tokyo (Fig. 1). The event demonstrated that an earthquake with a moment magnitude less than 7 could result in serious damage near the epicenter, namely 40 fatalities, 2,900 injuries and 3,473 houses damaged including 395 either partially or totally collapsed. In addition, railway and highway embankments suffered an unexpected degree of failure.

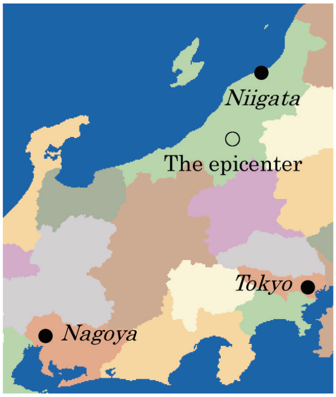

Figure 1. Map of Japan the site location.

Along the railway lines of East Japan Railway Company excluding the Shinkansen lines, embankment deformation and failure were observed at 26 places. At 6 of these places, complete embankment failure resulted in tracks hanging like ladders. Notable damage occurred mostly along the Joetsu line operated near the epicenter. The damage is characterized by its scale and range especially for earth structures in comparison to reinforced concrete structures. Large amounts of precipitation caused by typhoon No. 23 on October 20 before the earthquake may have worsened the seismic damage.

2 NEAR THE PORTAL OF THE TENNO TUNNEL OF THE JOETSU LINE

2.1 *Damage to the embankment*

As is shown in Photo 1, the earthquake caused railway embankment failure near the tunnel portal, especially the embankment for a Niigata track (down line) on the undercut slope, which was built on the valley side formed by erosion from the Shinano River. A national highway runs on the alluvial terrace over the tunnel of a Takasaki track (up line) adjacent to the down line. The ground bearing the embankment of the down line in the region is characterized as dipping planes, so to speak, sloping heavily toward the river and then easily gathering water during rainfall.

Photo 1. Overview of failure of the embankment.

The surface of the embankment had failed in the past, namely in 1981 and 1999, and slope protection measures were adopted, such as restraining rail piles, earth retaining walls and free-frame work. However, the embankment slope has shown repeated small-scale sliding because the bedrock itself dips to the river and because it is difficult to fully embed the foundations into the ground due to the steep slope and narrow space. The total soil quantity that failed during this earthquake last fall was estimated to be 9,900 m^3.

2.2 *Review of remedial measures*

Colluvium fell from the track of the down line and was deposited on the slope about 70 to 80 m long and 50 m wide. Slope failures occurred continually in the vicinity of the restoration site, which endangered approaching from the riverside. In view of the seriousness of the damage, failure-restraining structures with piles or bridge construction was originally considered to provide resistance to earthquakes and precipitation (Fig. 2). However, it takes approximately six months to build such structures. As restoring the railways, a means of mass transit, was considered to be in the public's interest, early resumption of operation and guarantee of safety were defined as fundamental goals. It was then decided to give priority to re-opening the up line, which had suffered less serious damage.

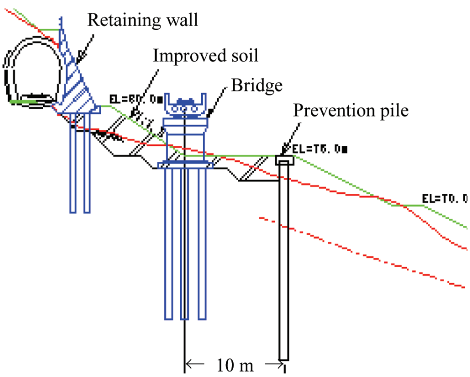

Figure 2. Remedial plan with bridge.

The damaged site was on a steep slope, and bringing in large heavy equipment such as pile drivers would require large-scale temporary work such as building a platform and acquiring piles, which was also difficult. Therefore, a method to restore the embankment to the level of the track was finally selected. A plan to remove all the colluvium and construct the embankment at the designated stable gradient would likely require embankment material of more than 10,000 m^3 and a construction period of more than two months. In order to reduce the volume of embankment material, which would have a great impact on the construction period, the RRR method was adopted (Fig. 3).

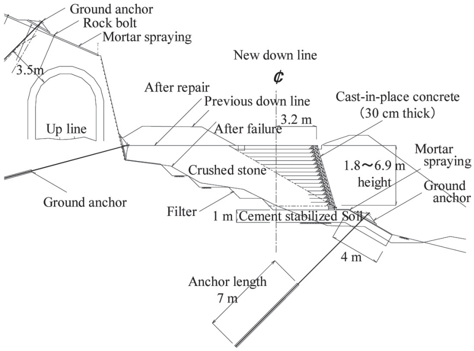

Figure 3. Determined remedial plan.

3 INVESTIGATION AND DESIGN

3.1 *Evaluation of soil strength*

Based on the soil boring logs at the damaged site, steep hill deposits lay around the up-line tunnel. The soil was estimated to have an *N*-value of 25 to 30 and the internal friction angle ϕ was set at 35° according to the formula $\sqrt{15N} + 15$, where specific weight was set at $\gamma = 18$ kN/m^3. The thickness of slid clod was approximately 5 m and cohesion c was then assumed to be 5 kN/m^2. For the down-line section, reverse analysis was carried out for the ground shape after slip failure under the condition of a safety factor of 1 (Fig. 4). As a result, the internal friction angle of colluvium on the down-line section was set at 20°C. (Cohesion c was also set at 5 kN/m^2).

3.2 *Review of ground anchors*

By introducing ground anchors with a strength of 150 kN/m on both the upper and lower levels of the tunnel to repair the up-line section, a minimum safety factor of 1.31 was obtained in the cross section shown in Fig. 3; that is, a normally required safety factor of 1.2 was secured.

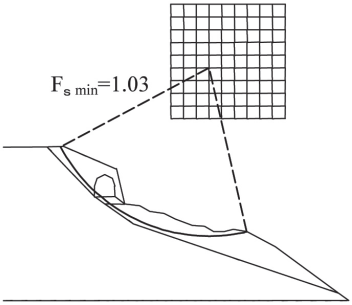

Figure 4. Result by reverse analysis.

On the down-line section, where the embankment was to be reinforced with the RRR method, introducing ground anchors with a strength of 150 kN/m on every level secured the normally required safety factor of 1.4, because a minimum safety factor of 1.6 was expected to be obtained in the cross section shown in Fig. 3. The force per anchor rod was 600 kN (= 150 × 4) in either case if the pitch between anchor rods was assumed to be 4 m.

3.3 *Design of Rreinforced embankment*

As the physical properties for the embankment material, a specific weight per volume γ of 20 kN/m^3, an internal friction angle ϕ of 30°C (cohesion c = 0), a design strength of reinforcing material T_a of 31 kN/m and a vertical interval of reinforcing material (geogrids) of 30 cm were specified and a cross section with the designated safety factor was determined as shown in Fig. 3. For the retaining wall, a design concrete strength σ_{ck} of 21 N/mm^2 and a thickness of 30 cm were specified.

4 CONSTRUCTION AND EXECUTION MANAGEMENT

The construction procedure for the reinforced embankment is shown in Fig. 5

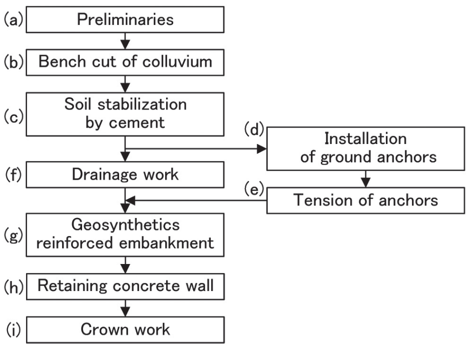

Figure 5. Construction flow.

4.1 *Soil stabilization using cement*

To reinforce the bearing stratum of reinforced embankment and to secure the operation yard for heavy equipment, the soil was stabilized for a depth of 1m by applying cement-type solidifiers with a blending proportion of 150 kg/m^3. The quantity of solidifiers was so determined that a coefficient of subgrade reaction K_{30} of 70 MN/m^3 could be achieved according to plate loading tests. A one-ton pack of additive was supplied over an area of 6.5 m^2 because the depth of soil reinforcement was one meter. The soil was mixed with solidifiers in the area using a backhoe (Photo 2).

Photo 2. Soil stabilization by cement.

4.2 *Ground anchor work*

After the soil was stabilized with cement, a soil platform for anchor work was built for installing fourteen 15-m-long ground anchors with pretension of 600 kN per rod at intervals of 4 m. Drilling angle was 15° upward to the normal slope line (Photo 3). After the drilling boreholes were washed out with fresh water to remove slime and other materials, grouting was carried out while carefully removing water and air from the casing pipe until the grout material filled the boreholes and was discharged.

Photo 3. Installation of ground anchor.

After confirming that grout strength exceeded 24 N/mm^2, pre-stressing and anchorage steps followed. The functioning of anchors was verified for 14 anchor rods by tests before anchorage.

4.3 *Drainage work*

To remove the seepage discharging from the ground and the water infiltrating into the embankment, perforated underdrain pipes with a diameter of 65 mm were installed on bench-cut ground berms, which were lined with crushed stone (C-40) and connected to the drainage pipe in front of the reinforced embankment. Filter drainage layers 0.5 m wide and 4 mm thick were laid at the boundary between the ground and the embankment at intervals of 2 m. Material against sand outflow was attached throughout the ground to prevent fine soil particles from entering the crushed-stone embankment from the ground (Photo 4).

Photo 4. Drainage work.

4.4 *Embankment reinforcing work*

As planar reinforcement material, high-strength vinylon geogrids were placed on each layer in the embankment at vertical intervals of 30 cm with no loosening. The reinforcement material was laid with an overlap of 10 cm at joints in the longitudinal direction on the embankment. To ensure slope stability during construction of the embankment, L-shaped wire cages were introduced for temporary restraining. Sheets with a thickness of 10 mm were attached in the cages to prevent the embankment material from spilling out (Photo 5).

As embankment material, artificially graded crushed stone (C-40) was purchased, delivered in 10-ton dump trucks to temporary storage and transported in crawler vehicles to the embankment construction site. Then, the material was spread by backhoes and compacted with 4-ton rollers. During the embankment work, density tests were conducted by the sand replacement method, resulting in a degree of compaction of 95%, where the standard minimum degree is 90%. According to plate loading tests conducted at the crown of the embankment, the coefficient of subgrade reaction K_{30} was 139 to 184 MN/m^3, satisfying the standard of 110 MN/m^3.

Photo 5. Geosynthetics reinforced embankment.

4.5 *Concrete wall work*

After placing a 900 mm-thick concrete foundation, a 300 mm-thick concrete wall was placed. At the base of the wall, 1-m-long D22 anchor bars were installed at an embedded depth of 600 mm and then formwork was carried out. A polyvinyl chloride pipe extended with sockets was installed for drainage. The wall thickness was 300 mm and relatively thin compared with the wall height of approximately 5 m. Spacers on one side of the formwork were, therefore, firmly welded to anchor bars to prevent the formwork from bulging.

5 CONCLUDING REMARKS

As the existence of a large slip surface under the national highway and the tunnel of the up line was of great concern, borehole inclinometers and extensometers were installed in the restoration section to allow for dynamic field observations during construction. Only minor displacements were observed, which subsided during construction, and the work was completed without any problems (volume of embankment material: 1,767 m^3, scale of concrete wall work: 81 m^3).

Restoration from damage is conventionally temporary because of its emergency nature, and full-scale measures satisfying permanent requirements are taken later. At the project site under study, the adopted RRR method satisfies the requirements even on the bearing stratum composed of colluvium on a steep slope. A permanent structure with an approximate length of 60 m and maximum height of 6.9 m was completed in approximately one month by a method that could shorten the construction period through the reduction of resource quantities and due to favorable weather conditions (Photo 6).

Photo 6. View of the completed structure in snow.