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Passive force-deflection curves for transition zone backfills for high-speed rail bridge abutments

Curvas pasivas de fuerza-desviación para rellenos de zona de transición para pilares de puentes ferroviarios de alta velocidad

K.M. Rollins and R. Black
Brigham Young University, Provo, USA

D.E. Schwicht
Shannon and Wilson, Seattle, USA

A. Shamsabadi
California High-Speed Rail, Sacramento, USA

ABSTRACT: To minimize differential settlement adjacent to bridge abutments for the California High Speed Rail, a transition in backfill stiffness will be placed adjacent to bridge abutments. Cement Treated Gravel (CTG) will be placed adjacent to the concrete abutment, followed by a zone of compacted gravel, followed by typical silty sand embankments. To investigate the passive force-displacement relationships provided by this transitional backfill during earthquakes, large-scale lateral abutment load tests were performed. To investigate the effect of skew angle on the passive force, which has been shown to develop lower resistance with increasing skew angle, tests were performed with skew angles of 0 and 30º. The peak passive force for the transitional backfill was about 2.5 times higher than that predicted with the Caltrans design method for sand backfill. However, passive force developed with displacement of about 3% of the abutment wall height similar to a conventional granular backfills. The skew angle had much less effect on the peak passive force for the transitional backfill than for conventional granular backfills. Field measurements indicate that the CTG backfill largely moves with the abutment while shear failure and heaving largely occurs in the granular backfill behind the CTG.

RÉSUMÉ: Para minimizar el asentamiento diferencial adyacente a los pilares del puente para el tren de alta velocidad de California, se colocará una transición en la rigidez del relleno adyacente a los pilares del puente. Grava tratada con cemento (CTG) se colocará adyacente al pilar de concreto, seguido por una zona de grava compactada, seguido por los típicos diques de arena limosa. Para investigar las relaciones de fuerza-desplazamiento pasivas proporcionadas por este relleno transitorio durante los terremotos, se realizaron pruebas de carga de pilar lateral a gran escala. Para investigar el efecto del ángulo de sesgo en la fuerza pasiva, que se ha demostrado que desarrolla una resistencia más baja al aumentar el ángulo de sesgo, se realizaron pruebas con ángulos de sesgo de 0 y 30º. La fuerza pasiva máxima para el relleno transitorio fue aproximadamente 2,5 veces mayor que la predicha con el método de diseño Caltrans para el relleno de arena. Sin embargo, la fuerza pasiva se desarrolló con un desplazamiento de aproximadamente el 3% de la altura de la pared de apoyo similar a un relleno granular convencional. El ángulo de sesgo tuvo mucho menos efecto en la fuerza pasiva máxima para el relleno transitorio que para los rellenos granulares convencionales.Il backfill CTG si sposta in gran parte con il moncone mentre il cedimento di taglio e il sollevamento si verificano in gran parte nel backfill granulare dietro il CTG

Keywords: High-Speed Rail, Passive Force, Transition Zone, Cement Treated Aggregate, Gravel

1 INTRODUCTION

High-speed rail track experiences accelerated degradation or differential settlement in zones of transition, such as at bridge abutments. This degradation is due to a difference in stiffness between the bridge (often pile-supported) and the approach or departure fill (often compacted sand or gravel) (Paixão et al. 2013). To reduce the differential settlement in these transition zones, California High-Speed Rail (CHSR) has designed a bridge abutment with a transition zone consisting of cement treated gravel (CTG) as a stiffness transition from the bridge to compacted gravel to minimize the differential settlement experienced in the transition zone. Although passive force-deflection relationships are well defined for conventional compacted backfill materials (Rollins and Cole, 2006; Shamsabadi et al. 2007), no test results are available to define the passive force-deflection behavior for transition zones with CTG between the bridge abutment and the compacted gravel backfill.

In addition, many of the bridge abutments for California High Speed Rail will be skewed relative to the underlying roadways. Abutment skew angle (θ) is the angle of the back wall of the abutment relative to a line perpendicular to the direction of travel. A large number of small- and large-scale tests have shown that skewed abutments develop significantly lower passive resistance than non-skewed abutments (Rollins and Jessee 2013; Marsh et al. 2013, Franke et al. 2013 and Frederickson et al. 2017) with backfills consisting of sands or gravels. Rollins and Jessee (2013) proposed the use of a skew reduction factor (R_{skew}) to account for reduced passive resistance as a function of skew angle. Based on all available test data, Shamsabadi and Rollins (2014) defined R_{skew} with the equation

$$R_{skew} = \frac{P_{p-skew}}{P_{p-no\ skew}} = e^{\left(\frac{-\theta}{45°}\right)} \quad (1)$$

for backfills composed of sand or gravel.

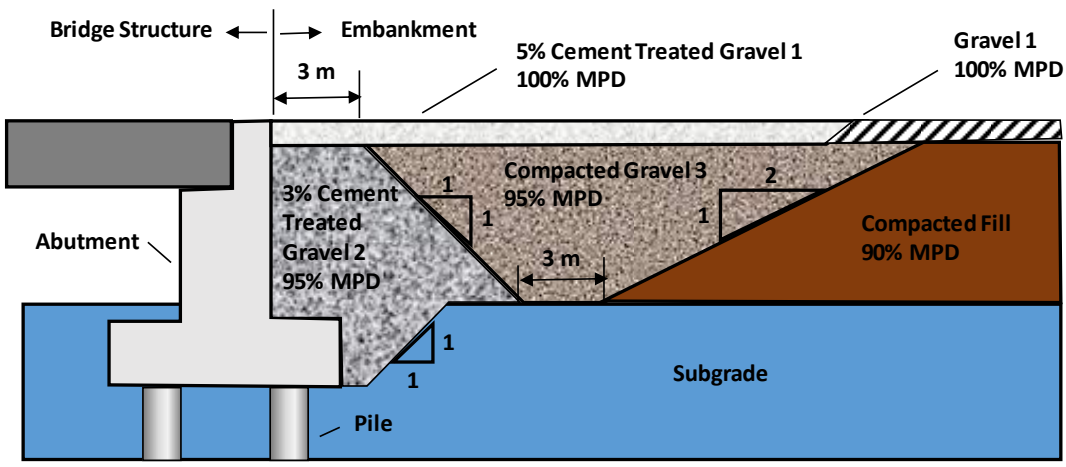

Figure 1. Schematic profile drawing showing transition section at bridge abutments proposed for California High Speed Rail project (Note: MPD is Modified Proctor Density).

Equation 1 predicts a reduction in passive force of about 50% for a 30º skew angle. Unfortunately, transitional backfills with CTG and compacted gravel zones have never before been tested for skew angle passive capacity reduction. However, small-scale abutment tests with low strength flowable fill backfills (unconfined compressive strength of about 400 kPa) showed little to no reduction in passive force with skew angle (Wagstaff, 2015). As a result,

there is considerable uncertainty about the influence of skew angle on passive resistance for the transitional backfills proposed for California High Speed Rail. For seismic regions, such as California, passive force-deflection relationships for backfill behind bridge abutments have a significant effect on bridge performance. To investigate the effect of transitional zones with CTG backfill on passive force-deflection relationships and the reduction in passive force with skew angle, a series of full-scale passive force tests were conducted in this study.

2 TEST GEOMETRY AND MATERIAL PROPERTIES

Passive force tests were performed without any skew (0º skew) and with a 30º skew. This plan provided basic passive force-deflection data for the transition zone backfill with the 0º skew case. Subsequent testing with the 30º skew abutment provided guidance on the potential reduction in passive force with skew angle.

2.1 Test Geometry

Plan and profile drawings showing the layout for the two full-scale tests are provided in Figure 2. A pile cap 3.35 m wide by 1.68 m. high was used to simulate a bridge abutment back wall. North of the pile cap, a transitional zone of CTG was compacted against the pile cap and extended 3 m behind the backwall at the surface with a 1H to 1V slope extending to the base of the pile cap. North of the CTG zone, a zone of Type 3 gravel was compacted with a base width of 3 m followed by a slope at a 1H to 1V. The backfill material was compacted to a depth of 1.83 m to extend 0.15 below the base of the pile cap. The was done to allow a log spiral failure surface to full mobilize within the Type 3 gravel zone.

The existing test site conditions required some alterations to the geometry of the California HSR design including the deletion of the uppermost layer of cement treated Type 1 gravel. These alternations are not expected to materially affect the measured passive force or skew reduction factors determined from the testing.

To create a 2-D or plane strain failure geometry typical of a wide approach fill, the concrete block walls supporting the excavation on the east and west sides were lined with plywood sheeting. Then, two layers of plastic sheeting with oil between them were placed against the plywood to create a low-friction interface to minimize side friction. A 30º skew wedge composed of reinforced concrete was attached to the front of the pile cap for the 30º skew test. The wedge was placed on a timber platform with steel pipe rollers to decrease friction on the base of the wedge for the test.

2.2 Material Properties

The gradation range specified by California HSR for the CTG with Type 2 gravel and the Type 3 gravel are shown in Figure 2(a) and (b), respectively, along with the average gradation of the gravels actually used in this study.

For both backfill material types, tests were performed to determine the modified Proctor moisture-density relationship. Testing with the CTG was performed at the specified cement content of 3% by mass. The modified Proctor maximum dry density for the Type 2 (CTG) backfill was 21.7 kN/m^3 with an optimum moisture content of 6.5%, while the maximum dry density for the Type 3 (gravel) was 21.2 kN/m^3 with an optimum moisture content of 6.5%.

Granular materials were stockpiled onsite and the Type 2 gravel was mixed with 3% cement and water using a continuous concrete mixing truck. Mixed CTG and Type 3 gravel zones were then compacted simultaneously in 15 cm lifts behind the pile cap. Because of limited space, compaction was accomplished using a combination of jumping jack compactors and a vibratory trench roller.

To assure compliance with California HSR specifications, density and water content in the compacted backfill were consistently monitored

using nuclear density gauge tests. The average relative compaction was 95% and 97.4% for the CTG and Type 3 gravel backfills, respectively with average compaction water contents of 7.9% and 6.6%, respectively.

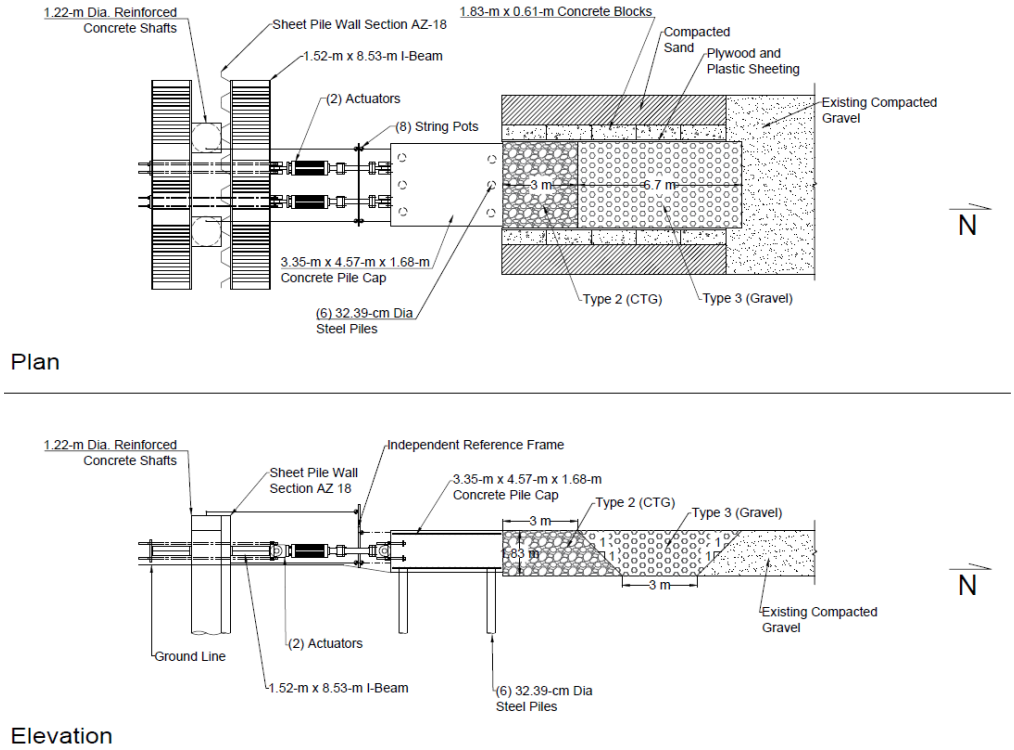

Figure 2. Plan and elevation views showing layout of the simulated abutment, backfill soil and loading system.

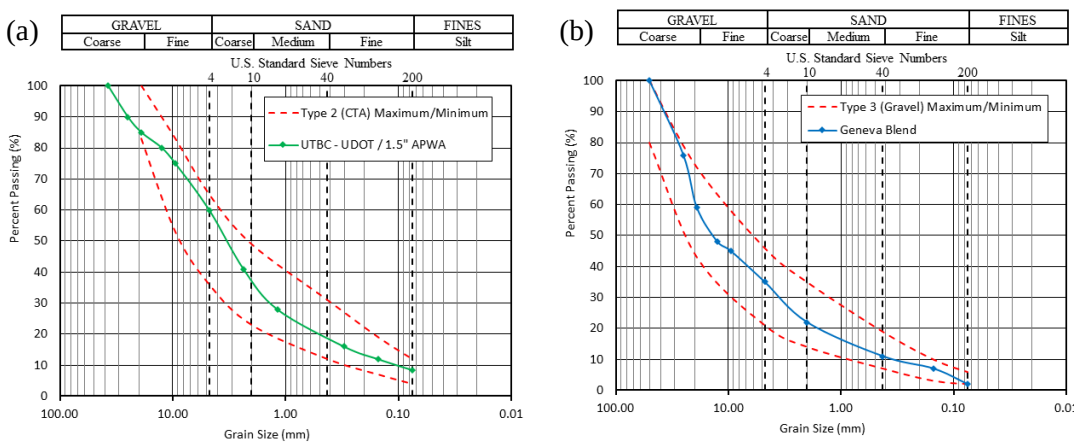

Figure 3. California HSR particle size distribution curve ranges and actual curves for (a) Type 2 Cement Treated Gravel (CTG) and (b) Type 3 Gravel without cement.

CTG test specimens were compacted into Proctor test molds at 95% relative compaction during installation of the backfill for the 0˚ and 30˚ test configurations. The test cylinders were extruded using a hydraulic extruder immediately after casting. After 48 hours, the cylinders were moved to the fog room where they cured Seven days after casting, the cylinders were soaked in a water bath at room-temperature for a minimum of three hours, then capped with gypsum. Compression testing was then performed on the specimens to determine the unconfined compressive strength. Using the 0.2% offset method, the average UCS for the test cylinders was 9.3 MPa.

3 LOADING PROCEDURE AND INSTRUMENTATION

As shown in Figure 2, load was applied to the simulated abutment (pile cap) using two 2600 kN hydraulic actuators controlled by a portable pump and generator system. Applied load was adjusted to induce longitudinal defletion with mimimal pile cap rotation The actuators reacted against a 1.5 m deep beam which reacted against two 1.22 m diameter drilled shafts and an AZ-18 sheet pile wall that extended 10 m into the ground. The reaction system was tied together with eight tie-rods that connected the front and back beams.

Deflection of the pile cap was measured using four string potentiometers at the four corners of the back face of the cap. The string pots were attached to an independent reference frame. Prior to testing, a grid consisting of 0.6 m squares was painted on the surface of the backfill. A level survey was conducted at the grid points before and after loading to monitor the heave of the surface produced by lateral loading to understand the failure mechanism.

The abutment passive force tests were performed with a deflection controlled approach. Load was applied to produce deflection increments of about 6.35 mm until failure. Each test was conducted seven days after installation of the backfill to allow the CTG to cure prior to testing. A lateral load test was performed prior to backfill placement to obtain the baseline resistance provided by the pile cap. Then, after backfill placement another lateral load test was performed to obtain the total resistance. The difference between the total and baseline curve then provided the longitudinal resistance provided by the transitional backfill.

4 TEST RESULTS

A suite of load versus deflection curves obtained from the test with the 0˚ skew abutment is provided in Figure 4. The total load is the sum of the two acuator loads while the pile cap deflection is the average of the deflection measured by the four string pots. The baseline load versus deflection curve is relatively linear in shape because gaps have formed under the base of the cap and around the support piles from previous loading. Therefore, most of the lateral resistance is flexural resistance provided by the piles themselves.

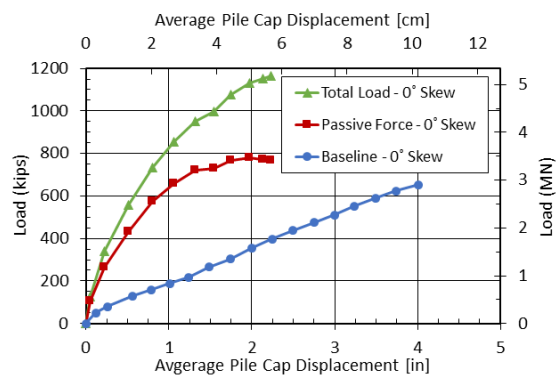

Figure 4. Total force, net longitudinal force and base-line force versus displacement for 0˚ skew test.

The net longitudinal load or passive force deflection curve has a hyperbolic curve shape and peaks at a deflection of about 50 mm. This

represents a deflection equal to about 3% of the abutment wall height, *H*. This deflection is within the range of 3 to 5% of H observed in previous full-scale tests backfill (Rollins and Cole, 2006).

A color contour plot showing the variation of the measured backfill heave for the 0˚ skew passive force test is provided in Figure 5. Backfill heave was insignificant within the CTG zone within the first 3 m behind the pile cap but increased markedly behind the CTG within the compacted Type 3 gravel. This result suggests that the relatively stiff CTG zone was basically moving as a block along with the pile cap and that shear failure and the associated heave were occuring within the Type 3 gravel zone. Shear failure planes appeared to be daylighting near the back of the Type 3 gravel zone.

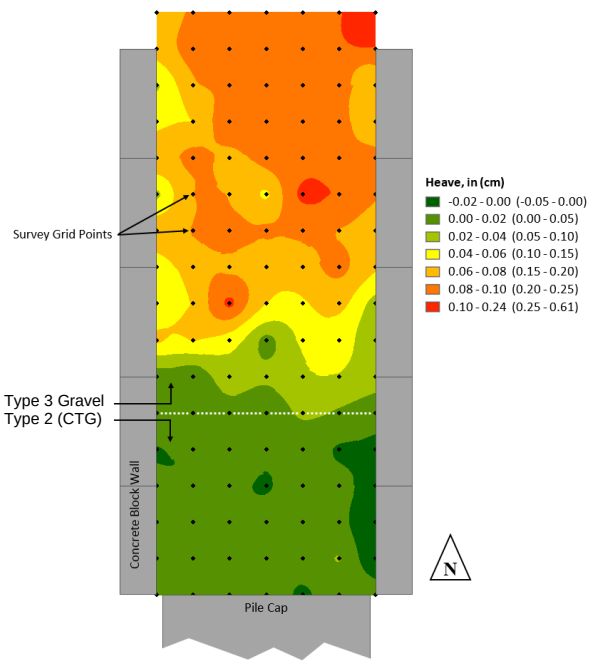

Figure 5. Color contours of backfill heave during 0˚ skew passive force test.

According to California Department of Transportation design procedures, the ultimate passive force on a bridge abutment, P_{ult}, can be computed using the equation

$$P_{ult} = (0.239\ MPa)\ A_b\ (H/1.68) \qquad (2)$$

where A_b is the area of the backwall in square meters and *H* is the height of the abutment backwall in meters. Using Eq. 2, a P_{ult} of 1346 kN would be predicted while the measured P_{ult} for the transition zone backfill is 3471 kN. Therefore, the P_{ult} for the transition zone is 2.57 times higher than that for a typical compacted sand backfill.

Passive force versus deflection curves for the 0˚ and 30˚ skew tests are compared in Figure 6. For the 30˚ skew test the passive force was obtained by mutiplying the net longitudinal force by the cosine of the skew angle, θ, to resolve the force perpendicular to the abutment backwall as proposed by Burke (1994). Passive force for the 30˚ skew test is mobilized with a displacement equal to 2.75% of the wall height, *H*.

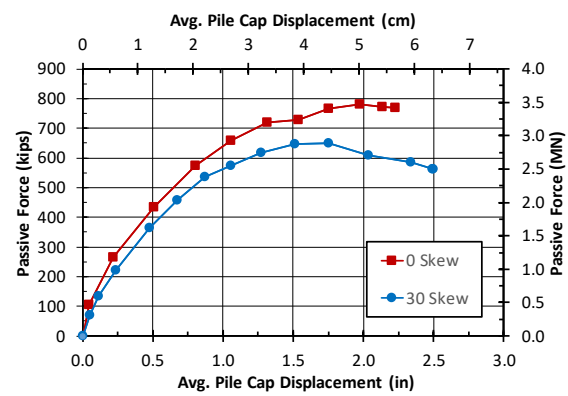

Figure 6. Passive force versus deflection curves for 0˚ and 30˚ skew abutment tests.

At a skew angle of 30º, R_{skew} is about 0.83 for the transitional backfill whereas R_{skew} is predicted to be 0.51 for conventional sand and gravel backfills based on Eq. 1. These test results clearly show that there is less effect of skew angle on the passive resistance for the transitional zone with the CTG backfill zone investigated in this study.

One possible explanation for the discrepancy is that the interface friction between the pile cap and the cement treated gravel is much higher owing to cementation than the interface friction

between the pile cap and conventional granular material. Typically, the wall friction between a concrete abutment backwall and adjacent granular backfill may be 60 to 80% of the friction angle of the backfill (Potyondy, 1961). However, for the CTG-pile cap interface, the interface strength is at similar to the strength of the CTG. Likewise, because the Type 3 gravel is compacted against the CTG zone prior to curing, a rough, cemented interface likely develops which increases the strength of this interface as well.

Analyses indicate that reasonable prediction of the measured passive force can be obtained for the 0˚ skew test using the log-spiral failure mechanism and assuming that shear failure occurs entirely within the Type 3 gravel. In this analysis the friction angle of the Type 3 gravel was assumed to be 46˚ based on previous in-situ direct shear tests of comparable gravel backfill (Fredrickson et al. 2017). In addition, the interface (wall) friction angle was assumed to be equal to the friction angle of the gravel backfill because of the rough, cemented interface.

5 CONCLUSIONS

Based on the field test results, the following conclusions can be made relative to the transition zone backfill for California high speed rail.

1. The peak passive force was about 2.5 times higher than that predicted with the Caltrans design method for sand backfill.
2. Peak passive force developed with displacements of 2.75 to 3% of the wall height, *H* in comparison to 3 to 5% of *H* for conventional granular backfills.
3. The skew angle had much less effect on the peak passive force for the transitional backfill than for conventional granular backfills. For example, the passive force reduction factor, R_{skew}, was only 0.83 for the 30º skew abutment in comparison to 0.51 for conventional granular backfills.
4. Field measurements indicate that the CTG backfill largely moves with the abutment and does not experience significant heave while shear failure and heaving largely occurs in the Type 3 gravel zone behind the CTG backfill.

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