

STIFFNESS AND ULTIMATE STRENGTH OF BRIDGE ABUTMENTS: SOIL-DEPENDENT MODEL

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ABSTRACT

Bridge abutments play an important role in the magnitude of earthquake-induced forces transmitted into the bridge structure. Many factors such as nonlinear soil behavior, soil properties, and abutment dimensions must be considered for realistic characterization of abutment-backfill interaction. However, for simplicity, in many existing models for the abutment capacity and stiffness, the effects of nonlinearity and properties of the soil are not considered. The main goals of this research program are to determine the abutment capacity and stiffness from field tests, using different soil types and to develop simplified soil dependent models to predict abutment behavior. In the first phase of the experiment, an abutment wall (without a foundation) was built at 50% scale of a prototype abutment, to study the longitudinal stiffness and strength of a backwall. Two different soil types will be used to characterize a range of soil properties to be expected behind bridge abutments. A proposed second phase of this research program will investigate the system effect on stiffness and strength of an abutment and evaluate the accuracy of a proposed model of the soil springs.

Keywords: abutments, bridges, experimental testing, soil type, ultimate capacity, stiffness

INTRODUCTION

Abutments are earth-retaining structures which support the superstructure at the ends of a bridge (Fig. 1) and provide resistance to deformation and earthquake induced inertial forces from the

bridge deck. Bridge abutments play an important role in the magnitude and distribution of earthquake-induced forces transmitted into the bridge structure. Factors such as nonlinear soil behavior, soil properties, geometry of an abutment, and soil-structure-interaction must be considered for a realistic characterization of abutment capacity and/or stiffness. However, for simplicity, in many existing abutment models for capacity and stiffness, the effects of soil nonlinearity and soil properties are not considered.

Most specifications and guidelines for earthquake design of bridges require that the abutment–soil system be included in the analytical model as a discrete equivalent linear spring. Current design practice in California makes use of the load-deformation curve established from the large scale abutment testing conducted at UC, Davis (Maroney 1995) and disregards the soil backfill conditions.

A review of typical bridge plans and the requirements presented in the Caltrans Standard Specifications (Caltrans, 1999), showed a tremendous variation in soil types used for structural abutment backfills and therefore load-deformation behavior in field conditions. In order to obtain a better understanding of the behavior of bridge abutments, an experimental research program is underway at the University of California, San Diego, funded by the California Department of Transportation (Caltrans). In this study, we characterized the range of soil properties to be expected behind bridge abutments and then planned field testing to focus on springs appropriate for abutment design as a function of soil type. The main goals of this research program are to determine the abutment capacity and stiffness from field tests, using different soil types and to develop simplified soil dependent models to predict abutment behavior. In the first phase of the experiment, an abutment wall (without a foundation) was built at 50% scale of a prototype abutment, to study the longitudinal stiffness and strength of a backwall. Two different soil types will be used to characterize a range of soil properties to be expected behind bridge abutments. A proposed second phase of this research program would investigate the system effect on stiffness and strength of an abutment and evaluate the accuracy of a proposed model of the soil springs.

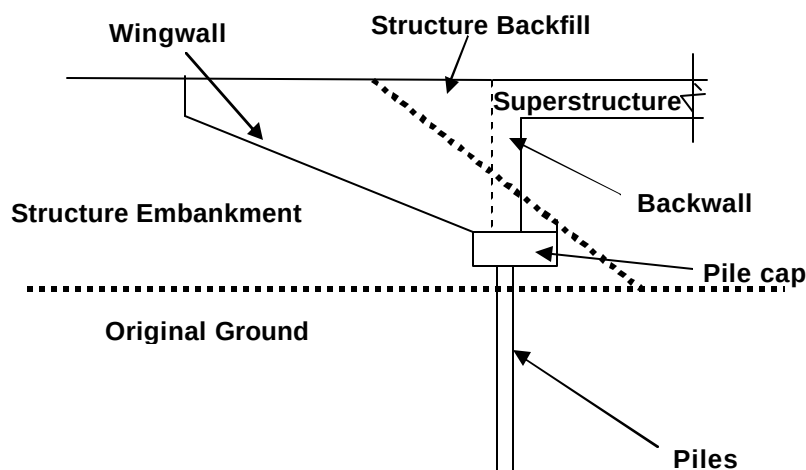


Fig. 1. Bridge Abutment,-Side Elevation

THEORY

The new design procedure considers the abutment backwall to be sacrificial and sheared off during strong earthquake in order to protect abutment piles from severe damage under

earthquake induced transverse forces (SDC 2001). Therefore the capacity of the bridge abutment in a seismic event is developed mainly from the mobilized passive pressure behind the abutment wall. A wide variety of methods are available to determine the capacity provided by passive pressure against the retaining structures. These methods include the Log Spiral (Terzaghi 1943, Terzaghi et al. 1996), Rankine, Coulomb, and Caltrans methods.

For cohesionless soils, the resultant horizontal force per unit width F_{ph} on a wall is given by the equation:

$$F_{ph} = 0.5gH^2K_p \cos d \quad (1)$$

where γ =total unit weight of the backfill; H =wall height; and δ =angle of wall friction. The Rankine, Coulomb, and Log Spiral methods all compute the passive pressure and resultant force using Eqs. (1), however, K_p varies for each method depending on the failure surface and force inclinations used. The Caltrans method computes the passive pressure using an empirical relationship based on experimental results.

The Log Spiral method is generally considered to be the most theoretically correct method for computing lateral earth pressure (Duncan and Mokwa 2001). The method accounts for the curved failure surface and for friction between the backfill and the wall (Fig. 2). Coulomb's method accounts for the wall friction, however it assumes a planar failure surface. As a result, values of K_p computed using the Coulomb theory are too high when the wall friction angle is greater than half of the backfill soil friction angle (Duncan and Mokwa 2001). Rankine's method assumes that the failure surface is planar and the wall friction is zero. As a result, Rankine's method tends to be conservative when predicting the passive pressure.

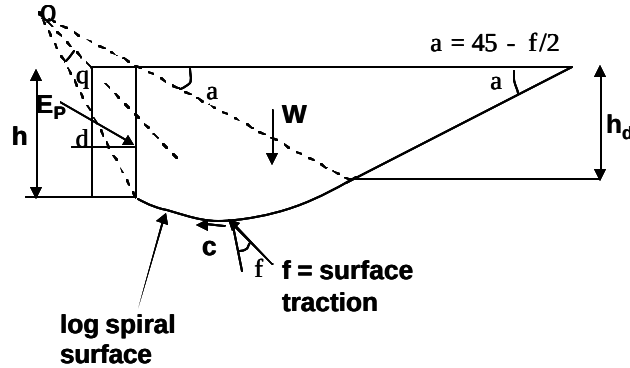


Fig. 2. Log Spiral Failure Mechanism

The Caltrans method is based on the results from large scale abutments testing at UC Davis (Maroney 1995). Caltrans (Seismic Design Criteria, 2004) suggests the initial longitudinal abutment stiffness to be equal to $20 \frac{\text{kip/in}}{\text{ft}}$. The initial stiffness shall be adjusted proportional to the backwall height as:

$$K_{abut} = k_i (= 20 .0 \frac{\text{kip/in}}{\text{ft}}) \times w \times \left(\frac{h_{abut}}{5.5} \right) \quad (2)$$

where, w is the width of the backwall. The Ultimate capacity of the abutment is given by Eq. (3). The maximum passive resistance of 5 ksf in Eq. (3) is based on the ultimate static force developed in large scale abutment testing at UC Davis. The height proportionality factor, $\frac{h_{abut}}{5.5 \text{ ft}}$, is based on the abutment test specimen height (5.5 ft) used at UC Davis. In Eq. (3), A_e is the effective abutment area. The passive pressure resisting the movement at the abutment increases linearly with the displacement, as shown in Fig. 3.

$$P_{abut} = A_e \times 5.0 \text{ ksf} \times \frac{h_{abut}}{5.5} \quad (3)$$

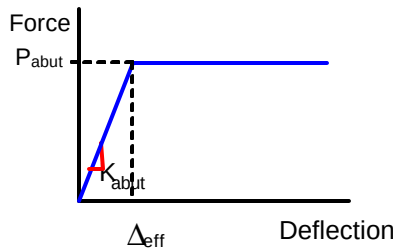


Fig. 3. Effective Abutment Stiffness

The ultimate resistance provided by passive pressure of two different soil types on the abutment wall with a height of 7.5 ft and a width of 15.5 ft, was computed using the described methods, and are summarized in Table 1. A comprehensive geotechnical investigation on test site is being conducted to accurately define the soil properties of the abutment backfill. Therefore, the properties of the soils were assumed for comparison purposes. The wall friction angle was assumed to be 50% of the backfill friction angle. The Caltrans method disregards the backfill soil type, thus it computed the same capacity for the abutment wall with different backfill material. However, the Log Spiral method estimated different abutment wall capacities for the two soil types of Table 1. As mentioned previously, Rankine's method underestimates the capacity.

Table 1. Comparison of methods for computing the passive pressure on abutment wall

Soil type \ Method	Log Spiral (kips)	Coulomb (kips)	Rankine (kips)	Caltrans (kips)
Sand ($\phi=38^\circ$, $c=0$, $\gamma=125$ pcf)	698	525	229	793
Clayey sand ($\phi=33^\circ$, $c=500$ psf, $\gamma=120$ pcf)	923	617	392	793

EXPERIMENTAL PLAN

Field Investigation

The current Caltrans Standard Specifications (Caltrans, 1999) contains gradation requirements and a compaction requirement of 95% relative compaction for the construction of an abutment backfill. An additional requirement which necessitates the backfill to be a sandy soil is the Sand Equivalent (SE) which must be greater than 20, determined per Caltrans Test Method 217. A review of several hundred bridge plans and the requirements presented in Caltrans Standard Specifications (Caltrans 1999), showed there were many different soil types used for structural backfills and embankments. Proper characterization of the soil types used for abutment backfills

and its potential variation in the field, is important to improve the current abutment design procedures. One-hundred bridges, from throughout the state, were selected to develop “typical” abutment backfill soil characteristics. Fifteen bridge sites were selected for field investigation. Each site included 1 to 3 soil borings with soil sampling, laboratory testing, CPT and Pressuremeter tests. For each site, representative soil types were defined from the soil samples in the upper 15 ft of the boreholes. The data was grouped into three key soil categories: sands, silty/clayey sands, and lean clay. Table 2 defines these three categories. The embankment of the abutment wall tested at UC Davis (Maroney 1995) was constructed from soil type “C”. Therefore, Soil types “A” and “B” will be used as the abutment backfill and embankment in this research project.

Table 2. Proposed Soil Type for Abutment Backfill

Soil Type	Grain Size Distribution			SE	PI
	75 mm	4.75 mm	Fines		
A (Sand)	100%	>80%	5-12	40+	<5
B (Silty/Clayey Sands)	100%	>90%	20-40	20-30	5-15
C (Lean Clay)	100%	100%	60-80	<10	>15

Field Test Facility

A soil-structure-interaction test facility has been constructed at the UCSD Englekirk Structural Engineering Center, at Camp Elliott. As shown in Fig. 4, the test facility consists of a refillable soil pit with dimensions of 70 ft by 70 ft and a depth of 20 ft. A movable reaction wall was constructed next to the soil pit. The movable reaction wall with a height of 16 ft consists of four 4-foot concrete reaction blocks which are post-tensioned to a deep pile foundation. The reaction wall has a moment capacity of 8000 kip-ft with up to 4 feet horizontal displacement. The facility is capable of investigating the factors that control the longitudinal resistance of bridge abutments.

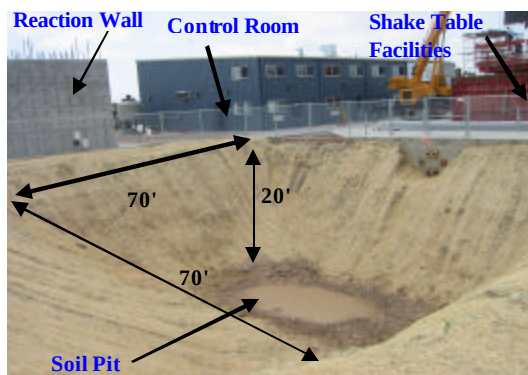


Fig. 4. Soil-Structure-Interaction Facilities, Camp Elliott, UCSD.



Fig. 5. Overall view of Abutment Wall During the Construction.

Overall Test Setup and Design of the Test Unit

The first phase of this research is being conducted on the performance of a component of a bridge abutment. An abutment wall (without a foundation) as an individual component of a bridge abutment was built at 50% scale of a prototype abutment. The key variables in this phase are the soil types and backfill height, as shown in Table 3.

Table 3. Bridge Abutment Research Program Test Matrix

Variables	Phase I				Phase II
	Test 1	Test 2	Test 3	Test 4	
Soil Type	B	B	A	A	System Test
Backfill Height	7.5 ft	5.5 ft	7.5 ft	5.5 ft	

In this experiment, the desired failure mode is geotechnical; not structural. Therefore the abutment wall, in the first phase, was designed and built to remain in the elastic range during these tests. The abutment wall, as shown in Fig. 5, will be used in all four tests in phase I.

The test setup is designed to model the longitudinal behavior of bridge abutments and restrict translational and rotational movements. As shown in Fig. 6, lateral load is applied to the abutment wall by five hydraulic actuators. The actuators are set up to restrain any upward movement of the abutment wall to develop a typical failure mechanism of bridge abutments. The test base, which consists of two concrete blocks, is post-tensioned to the reaction wall to prevent any movement of the test base. The abutment wall was placed on the test base, with no structural connection between the abutment wall and test base.

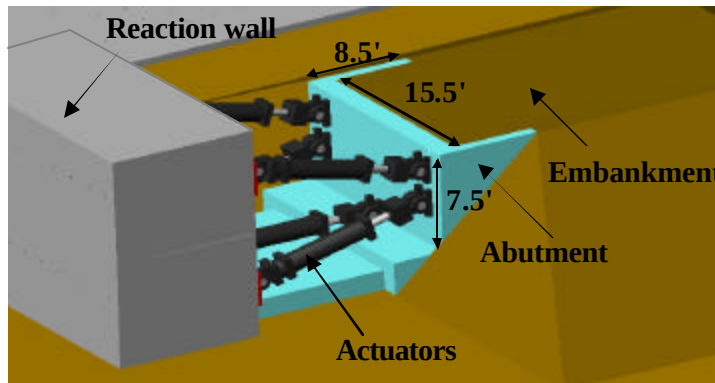


Fig. 6. Overall Test Setup for a Bridge Abutment, Phase I

A variety of instrumentation will monitor load, displacement, soil pressure, and strain during the testing. The displacement of the wall will be measured by four displacement transducers located on each side of the front face. Two inclinometers will be installed at front face of each wingwall to measure the rotation of the abutment wall. Also the difference in displacement measured at top and bottom of the backwall will be used to determine the rotation of the abutment wall. Twelve Pressure transducers will be placed throughout the backwall surface. The abutment wall has been instrumented with strain gauges mounted on reinforcing bars of the backwall and wingwalls. The first test is scheduled for October 2005.

Accurate prediction of the abutment behavior requires study of the entire abutment system, in addition to the aforementioned experiment. Therefore, in the proposed second phase, a large scale abutment system with the pile foundation embedded in soil will be tested. The results in the first phase will help to assess our understanding of the entire system through the experiment in the second phase.

SUMMARY AND CONCLUSIONS

A soil-structure-interaction test facility was developed to perform large scale tests on bridge abutments, using different soil types. The main goal of this research program is to develop an analytical method or procedure that can be used by practicing engineers to include soil properties in the estimation of bridge abutment capacity. In the first phase of the experiment, an abutment wall (without a foundation) was built at 50% scale of a prototype abutment, to study the longitudinal stiffness and strength of a backwall. Two different soil types will be used to characterize a range of soil properties to be expected behind bridge abutments. A proposed second phase of this research program will investigate the system effect on stiffness and strength of an abutment and evaluate the accuracy of a proposed model of the soil springs. A finite element study on the behavior of a bridge abutment will be performed, using a nonlinear soil model, and the results will be compared with test data to assess the proposed model.

ACKNOWLEDGMENT

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