

On design of retaining walls in seismic areas

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ABSTRACT: Retaining walls have failed either by sliding away from the backfill or due to combined action of sliding and rocking displacements, during earthquakes. Performance based design of the retaining walls in seismic areas must account for the likely displacements, in addition to calculating the usual factors of safety against failure in bearing, sliding and overturning. A realistic model for estimating dynamic displacement has been developed, which accounts for the combined action of sliding and rocking and takes into consideration, non-linear soil stiffness in sliding, and rocking, geometrical and material damping in sliding, and rocking, and coupling effects. This model was then used to calculate the displacement for several combinations of backfill and foundation soil conditions. The retaining wall displacements predicted by the proposed model were compared with the reported centrifuge test results on an 8-m high prototype gravity quay wall. The predicted displacements were on the conservative side.

1 INTRODUCTION

Retaining walls have failed during earthquakes by sliding away from the backfill or due to combined action of sliding and rocking displacements. Performance based design of the retaining walls in seismic areas must account for the likely displacements, the retaining wall may experience during an earthquake in addition to calculating the usual factors of safety against failure in bearing capacity, sliding and overturning. A realistic model for estimating the dynamic displacement must account for the combined action of sliding and rocking vibrations and should take into consideration the following:

- (i) Soil stiffness in sliding
- (ii) Soil stiffness in rocking
- (iii) Geometrical and material damping in sliding
- (iv) Geometrical and material damping in rocking
- (v) Any coupling effects for stiffness and damping.

Displacement based designs of rigid retaining walls have been proposed by Nandakumaran (1973), Richards and Elms (1979), and Wu and Prakash (2001). Draft Euro Code (8) on Seismic Design recommended permissible displacements due to sliding and rotation as $300 \times \alpha_{\max}$, where α_{\max} is the maximum horizontal ground motion due to earthquake.

A 2-D model using displacement (or strain) dependent stiffness and damping values for the soil was developed by Wu and Prakash (2001). This was then used to calculate the displacement for combinations of backfill and foundation soil conditions. The retaining wall displacements predicted by the proposed model were compared with the reported cen-

trifuge test results on an 8-m high prototype gravity quay wall. The proposed model was found to predict the displacement on the conservative side.

2 DISPLACEMENT CONTROLLED DESIGN

A simplified method for dynamic design of rigid retaining walls was proposed by Richards and Elms (1979). This method was based on Newmark's rigid sliding block analysis (1965) and Franklin and Chang's (1977) solution for upper bound permanent displacements for several natural and synthetic ground motions.

The assumptions for this analysis were:

- (1) The retaining wall is rigid,
- (2) The inertia forces due to the mass of the wall are included,
- (3) Only the sliding of the wall and dry backfill is considered.
- (4) After the horizontal ground acceleration exceeds the yield acceleration, the wall moves away from the backfill until the velocity of the wall motion changes.
- (5) The backfill failure wedge moves as a rigid body with the retaining wall.

The details are described by Richards and Elms (1979) and Wu and Prakash (2001)

Nadim and Whitman (1984) developed a method to evaluate permanent rotation and sliding movements of gravity retaining walls with dry, cohesionless backfill. All elastic deformations were neg-

lected. The work previously done by Richards and Elms (1979) was extended to study the tilting effect on a wall. The assumptions are:

1. The foundation soil has a constant moment capacity below which no rotational movements take place. Once the moment capacity is reached, the foundation soil deforms plastically in rotation, as a rigid-plastic material.
2. The center of rocking is at a fixed point at the base of the wall.
3. When the active condition exists, a failure zone consisting of an infinite number of parallel planes, develops in the backfill. This assumption allows assumed continuity when the wall is tilting.

The resulting mathematical model led to a solution involving several coupled equations which require an iterative solution. The horizontal ground acceleration coefficient (N) initiating plastic rocking (N_{tilt}) and plastic sliding (N_{slid}) were evaluated. The lower value of either N_{tilt} or N_{slid} determined whether a sliding or rocking motion governed the displacement (D) of a wall during a particular earthquake. This displacement was then estimated. Nadim (1982) and Nadim and Whitman (1983) also developed a finite element solution for the mathematical model of the soil system and concluded the following:

1. Earthquake loading may result in a residual force on the wall, which may be as much as 30% greater than the static active force.
2. If the dominant frequency ratio of ground motion to the fundamental frequency of backfill is greater than 0.3, the amplification of motion in the backfill plays an important role in the permanent displacement of the wall.

Rafnsson (1991) developed a model for simulating the response of rigid retaining walls. This model consisted of a rigid wall resting on the foundation soil and subjected to a horizontal ground motion. Both material and geometrical damping in sliding and rocking motions were considered, (Rafnsson and Prakash 1994). The mathematical model of Wu (1999) is similar to Rafnsson's model. Soil nonlinearity is included in defining the following properties, both at the *foundation* and the *backfill soils*:

- (1) soil stiffness in sliding,
- (2) soil stiffness in rocking,
- (3) material damping in sliding,
- (4) material damping in rocking,
- (5) geometrical damping in sliding and
- (6) geometrical damping in rocking,

In Wu's model an equivalent sinusoidal motion used by Rafnsson was replaced by the random ground motion and thus signature of ground motion frequency was also evaluated.

3 WU'S (1999) MODEL

3.1 Assumption

Wu's model (1999) representing the motion of rigid retaining walls under different field conditions subjected to earthquake loading, is a 2-D model (Figure.1) which considers soil linearity and simultaneous sliding and rocking. Time domain solutions of permanent displacement have been computed for these ground motions.

Typical backfill and foundation soil conditions with saturated, moist and dry soil are listed in Table 1. Further details of this model are described in detail by Wu and Prakash (2001)

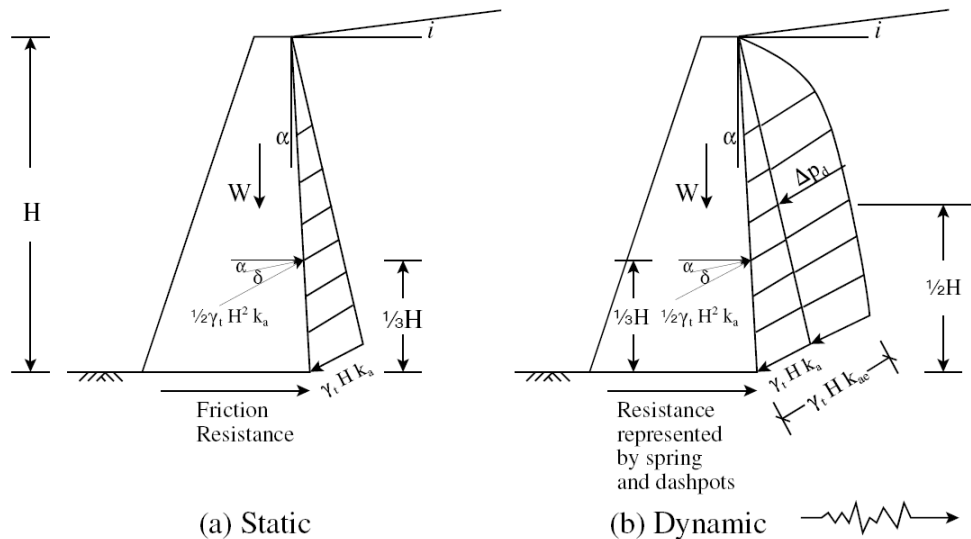


Figure 1: Force diagram of a wall with moist backfill and foundation soil subjected to a) static, and b) dynamic loading condition (Wu 1999)

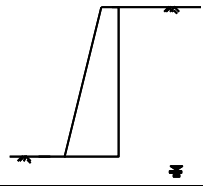
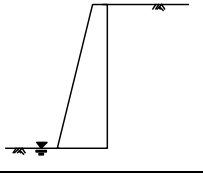
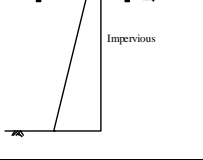
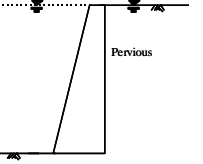
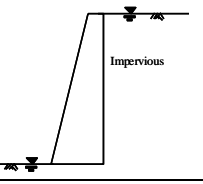
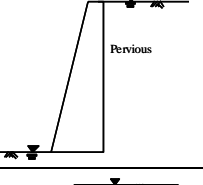
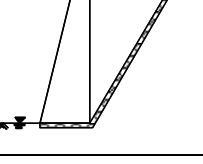
3.2 Typical Results

A wall 4m high (Figure 2a) with granular backfill and foundation soil is used for illustration of typical results subjected to Northridge earthquake of January 17, 1994 (Figure 2b). The displacements were computed on the assumption that the base width has been designed as for field condition 1 and displacements computed for Northridge earthquake for field

conditions 1 through 7. Nonlinear soil modulus and strain-dependant dampings are used in this solution.

Field conditions 1 through 4 have been specified in Eurocode 8 (1994). Conditions 5 through 7 as described are equally important field conditions. The magnitude of this earthquake is M 6.7 and peak ground acceleration is 0.344g. Figure 3 shows displacements of the 4m high wall under 7 field conditions. Table 2 lists these displacements.

Table 1: Loading conditions and corresponding parameters for dynamic displacements

	Field Condition	Parameters for	
		Static Condition	Dynamic Condition
	Condition 1 moist backfill moist foundation soil	$\gamma^* = \gamma_t$ $P_{ws} = 0$	$\gamma^* = \gamma_t$ $\Psi = \tan^{-1} \left(\frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	Condition 2 moist backfill saturated foundation soil	$\gamma^* = \gamma_t$ $P_{ws} = 0$	$\gamma^* = \gamma_t$ $\Psi = \tan^{-1} \left(\frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	Condition 3 submerged with impervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\Psi = \tan^{-1} \left(\frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$
	Condition 4 submerged with pervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\Psi = \tan^{-1} \left(\frac{\gamma_d}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 2 \times 7/12 \times \alpha_h \times \gamma_w \times H'$
	Condition 5 perched with impervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\Psi = \tan^{-1} \left(\frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	Condition 6 perched with pervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\Psi = \tan^{-1} \left(\frac{\gamma_d}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$
	Condition 7 perched with sloping drain	$\gamma^* = \gamma_{sat}$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat}$ $\Psi = \tan^{-1} \left(\frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$

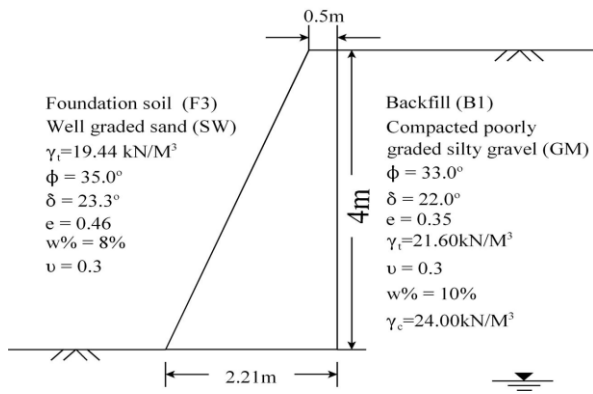


Figure 2a: Dimension of 4m high wall and soil properties used

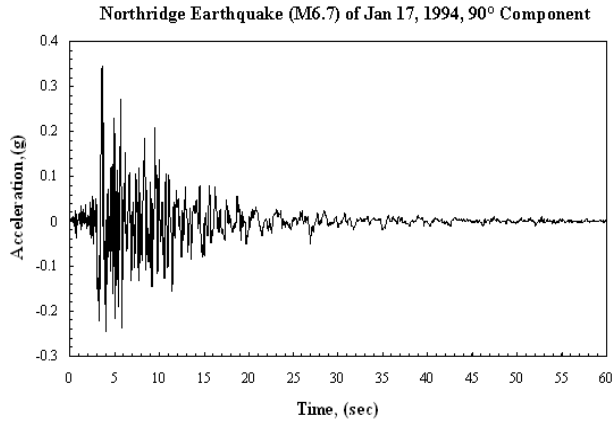
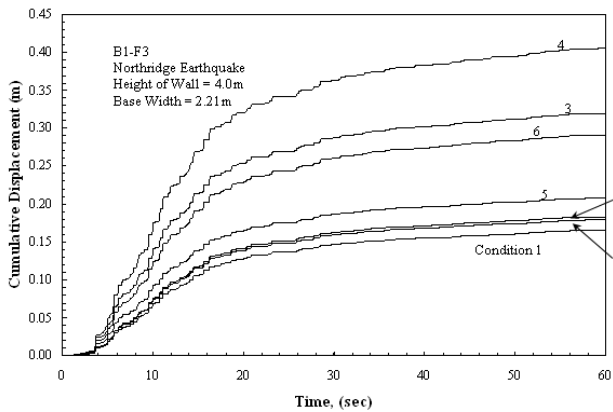


Figure 2b: Accelerogram of Northridge earthquake of Jan. 17, 1994, 90° Component

Figure 3: Computed displacement for 4m high wall and conditions 1 through 7 of Table 1

An examination of Table 2 indicated that sliding displacements (column 2) are close to 30 - 40 percent of the total displacement (Column 5). Maximum total displacements occur in field condition 4 i.e., submerged wall with pervious backfill. According to Eurocode, the permissible displacement is 10.32cm ($300 \times a_{max}$, where a_{max} is 0.344 in Northridge earthquake). Sliding displacement in conditions 3 and 4 exceed this value. It, therefore, appears that retaining walls be designed for permissible displacement for sliding only and then be built resting by a few degrees on the backfill. In this case this tilt is about 4° (3.67° maximum).



4m high wall for Field Condition 1 to 7

Displacement			%of Height		
Rocking	Total				
	m	m			
3	Column 4	Column 5	Column 6		
	0.1034	0.1656	4.1		
2	0.0667	1.61	0.1126	0.1793	4.5
3	0.1168	2.90	0.2023	0.3191	8.0
4	0.1492	3.67	0.2564	0.4055	10.1
5	0.0759	1.89	0.1319	0.2078	5.2
6	0.1076	2.62	0.1830	0.2905	7.3
7	0.0682	1.64	0.1148	0.1830	4.6

4 COMPARISON WITH MODEL TEST

Zeng (1998) conducted a centrifuge test on a gravity quay wall with loose dry sand as backfill and foundation soil (Figure 4) subjected to base shaking (Figure 5) for a prototype gravity wall 8m high and 4m wide. The gravity quay wall model was made of a solid aluminum block. The model earthquake was generated by a bumpy-road actuator.

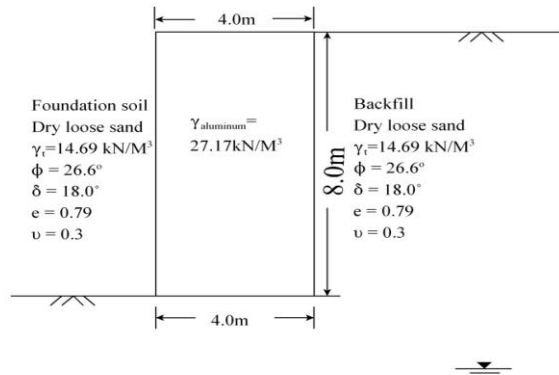


Figure 4: Wall section and soil Properties used in the centrifuge test

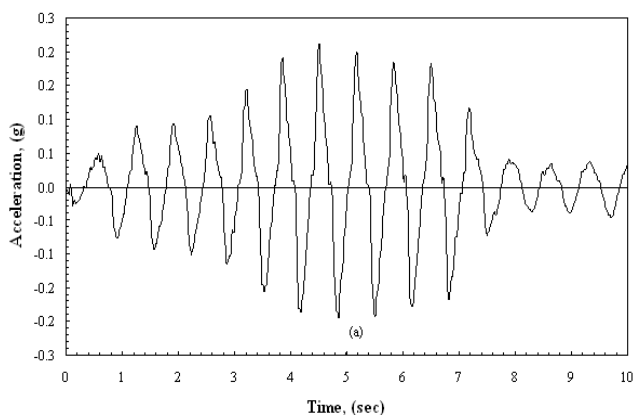


Figure 5: Comparison with model test: input ground motion for centrifuge test

Figure 6 shows the displacement computed by this model and the observed displacement in the centrifuge test. The displacement of the model wall after the test was approximately 0.17m. The computed sliding displacement, rocking degree, and total displacement in this computer program were 0.0870m, 1.20°, and 0.2469m, respectively. The computed displacement was 31% higher than the observed displacement. However, in general, this computed displacement is still valid and gives a conservative displacements estimate of the retaining walls during earthquakes.

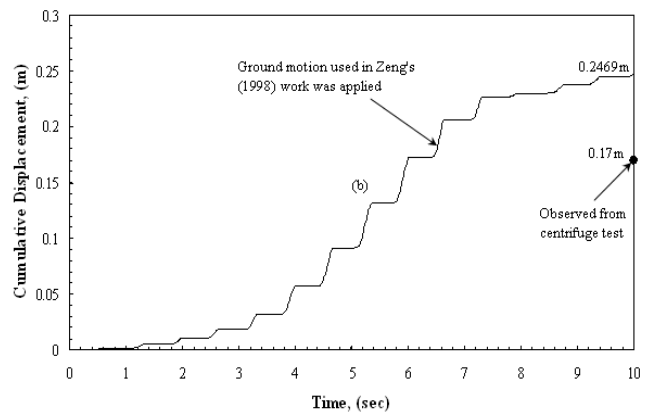


Figure 6: Comparison with model test: computed displacements compared with observed value by Zeng (1998)

5 TYPICAL DESIGN CHARTS

Wu (1999), developed comprehensive design charts for computed displacements of walls 4 m – 10 m high with several different foundations and backfill soils, and subjected to 3-different ground motions collected from El-Centro, Northridge and Loma-Prieta earthquakes (Table 3). These charts may be used for preliminary design of rigid retaining walls. For final design the displacement is computed by credible computer program.

6 RECOMMENDED DESIGN PROCEDURE

1. Determine the section for static loading condition with FOS=2.5 in bearing, and FOS= 1.5 for sliding and tilting as a rigid body.
2. Estimate the displacement from Wu's (1999). Design charts for comparable, backfill and foundation soils, and comparable ground motion.
3. Compare these displacements with permissible displacements as per Euro Code ($300 \times \alpha_{max}$)
4. If displacement in 2 is less than that in 3, then design is OK, or else revise the sections of the wall for lower FOS in (1).

Table 3: Cumulative Displacements for Walls 4 to 10m High with Granular Backfill and Foundation Soil and Field Conditions 1, 2 and 7 (Table 2) subjected to El-Centro, Northridge and Loma-Prieta earthquakes

H and B ¹ (m)	Field Cond.	Cumulative Displacement								
		El-Centro ²			Northridge ²			Loma-Prieta ²		
		Sliding m	Rocking Degree (m)	Total m	Sliding m	Rocking degree (m)	Total m	Sliding m	Rocking degree (m)	Total m
4 (1.94)	1	0.0956	2.92 (0.2039)	0.2994	0.0657	1.89 (0.1322)	0.1979	0.0053	0.12 (0.0084)	0.0137
	2	0.1006	3.09 (0.2156)	0.3163	0.0691	2.02 (0.1412)	0.2103	0.0057	0.13 (0.0092)	0.0150
	7	0.1048	3.23 (0.2253)	0.3301	0.0721	2.12 (0.1479)	0.2200	0.0060	0.14 (0.0097)	0.0157
5 (2.56)	1	0.1102	2.63 (0.2292)	0.3394	0.0752	1.70 (0.1487)	0.2239	0.0067	0.11 (0.0100)	0.0167
	2	0.1152	2.79 (0.2439)	0.3561	0.0793	1.82 (0.1590)	0.2383	0.0073	0.13 (0.0111)	0.0184
	7	0.1196	2.92 (0.2550)	0.3746	0.0823	1.91 (0.1668)	0.2492	0.0076	0.13 (0.0116)	0.0193
6 (3.17)	1	0.1219	2.44 (0.2556)	0.3775	0.0836	1.59 (0.1660)	0.2496	0.0081	0.12 (0.0121)	0.0202
	2	0.1269	2.59 (0.2709)	0.3978	0.0878	1.69 (0.1773)	0.2651	0.0087	0.13 (0.0134)	0.0221
	7	0.1316	2.70 (0.2832)	0.4148	0.0911	1.78 (0.1859)	0.2770	0.0090	0.13 (0.0141)	0.0231
7 (3.78)	1	0.1317	2.29 (0.2800)	0.4117	0.0909	1.50 (0.1828)	0.2737	0.0093	0.12 (0.0145)	0.0238
	2	0.1367	2.43 (0.2963)	0.4329	0.0944	1.60 (0.1952)	0.2895	0.0101	0.13 (0.0159)	0.0260
	7	0.1416	2.53 (0.3095)	0.4511	0.0982	1.67 (0.2041)	0.3023	0.0105	0.14 (0.0167)	0.0271
8 (4.39)	1	0.1401	2.17 (0.3028)	0.4429	0.0969	1.42 (0.1987)	0.2956	0.0106	0.12 (0.0166)	0.0272
	2	0.1451	2.19 (0.3196)	0.4646	0.1007	1.52 (0.2117)	0.3123	0.0113	0.13 (0.0182)	0.0295
	7	0.1502	2.39 (0.3336)	0.4839	0.1043	1.59 (0.2215)	0.3258	0.0117	0.14 (0.0191)	0.0308
9 (5.00)	1	0.1474	2.06 (0.3239)	0.4713	0.1021	1.36 (0.2141)	0.3162	0.0117	0.12 (0.0188)	0.0305
	2	0.1527	2.17 (0.3412)	0.4934	0.1058	1.45 (0.2271)	0.3329	0.0127	0.13 (0.0205)	0.0332
	7	0.1580	2.67 (0.3561)	0.5141	0.1095	1.51 (0.2375)	0.3470	0.0131	0.14 (0.0215)	0.0346
10 (5.61)	1	0.1543	1.97 (0.3437)	0.4980	0.1067	1.31 (0.2282)	0.3349	0.0130	0.12 (0.0209)	0.0340
	2	0.1597	2.07 (0.3614)	0.5210	0.1116	1.38 (0.2409)	0.3525	0.0139	0.13 (0.0229)	0.0369
	7	0.1653	2.16 (0.3769)	0.5422	0.1155	1.44 (0.2519)	0.3674	0.0144	0.14 (0.0240)	0.0385

¹H: height of wall, B: base width

²Permissible displacements for three earthquakes according to Eurocode = $300 \times \alpha_{\max}$

El-Centro = 300×0.349 (mm) = 0.1047m

Northridge = 300×0.344 (mm) = 0.1032m

Loma-Prieta = 300×0.113 (mm) = 0.0339m

7 CONCLUSIONS

The following conclusions are drawn:

1. A realistic displacement model for rigid retaining walls under earthquake condition has been developed.
2. The model can consider non-linear soil properties and any water condition behind the wall.
3. The predictions of actual displacements of a model are within reasonable agreement.
This is the most realistic model which can be adapted to analysis of bridge abutments also (Munaf. and Prakash, 2004).

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