Seismic stability of rock islands for bridge protection in coastal South Carolina

La stabilité sismique des îlots rocheux dans l'optique de la protection de ponts, dans la Caroline du Sud.

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ABSTRACT: The design for a major cable-stayed bridge to be constructed in seismically-active Charleston, South Carolina, included rock islands around the main span piers as protection from ship impact. Considering the seismic potential, a primary concern was the potential for instability of the rock island slopes during a major earthquake. This paper presents the modeling of the rock island and ship channel using the dynamic two-dimensional finite difference program *FLAC.*

RESUME: Le projet d'un grand pont étayé par câbles, conçu pour une zone d'activité sismique près de Charleston, South Carolina, compte sur la présence de plusieurs îlots rocheux à l'alentour des piliers de soutien principaux pour parer à d'éventuels chocs de navire. Mais vu le potentiel d'activité sismique, il a fallu tenir compte de l'instabilité possible de ces flancs de rocher en temps de tremblement de terre. Nous présentons un modelage numérique de l'îlot et du passage maritime basé sur le programme de différenciation dynamique finie en deux dimensions *FLAC*.

INTRODUCTION

With the exception of the 1811-1812 New Madrid sequence, the 1886 Charleston earthquake is the largest known event to have occurred in the central and eastern United States (CEUS). With a currently accepted moment magnitude (**M**) of 7.3 (Johnson, 1996), the 1886 Charleston event was felt throughout the eastern U.S. and in such distant locations as Boston, Massachusetts; Chicago, Illinois; Milwaukee, Wisconsin; Cuba, and Bermuda (Dutton, 1889; Bollinger, 1997; Stover and Coffman, 1993). Structural damage was widespread, extending as far as Alabama, Ohio, and West Virginia. A maximum Modified Mercalli (MM) intensity of X was experienced in the near-source region and liquefaction was extensive in the epicentral area Obermeier et al., 1985; Amick and Gelinas, 1991; Talwani et al., 1999).

For design of the new cable-stayed bridge that will span the Cooper River between Charleston to Mount Pleasant (South Carolina), the design seismic hazard was dominated by a repeat of the 1886 earthquake. Due, in part, to the seismic design criteria, the bridge will cost an estimated $600M+. The main span of the bridge will be the longest for a cable-stayed structure in North America at 471 m (1545 ft), and will include rock islands around the piers as protection from ship impact. Considering the seismic potential in the project area, a primary concern was the potential for instability of the rock island slopes during an earthquake. Such instability would result in damage to rock islands, as well as, cause rock island material to enter the nearby ship channel. It was recognized during design considerations that rock island material in the ship channel would cause significant disruption to the continual maintenance (i.e., dredging) of the ship channel.

This paper presents the seismic stability evaluation performed by the authors to: (1) identify a rock island and channel slope configuration that would not jeopardize the ship channel maintenance operation, and (2) to assist in determining the design length of the main span (S&ME, 2000). The seismic stability evaluation for the rock islands was performed using data collected during site-specific field exploration and laboratory testing. The conceptual design for the rock islands was modeled using the dynamic two-dimensional finite difference program *FLAC* (Itasca, 2000).

GEOTECHNICAL SITE CHARACTERIZATION

Charleston is located along the South Carolina coast in the continental United States. It lies within the Coastal Plain Physiographic province that is characterized by a sediment wedge overlying hard Paleozoic metamorphic rock or hard Pre-Cretaceous igneous and sedimentary rock. The Coastal Plain sedimentary wedge ranges in thickness from essentially zero at the Fall Line (i.e., the contact of the Coastal Plain province and the Piedmont province) to over 800 m (2500 ft) along the western South Carolina coast.

Local Charleston near-surface ground conditions generally consist of loose fine sands susceptible to liquefaction and very soft clays. These soils typically range from 7 to 15 m (about 25 to 50 ft) in thickness. A variety of profiles exist including sites of uniform sand or clay and sites with extensively interbedded layers of sand, silt, and clay. A significant increase in stiffness and strength occurs in the underlying formations of the Cooper Group (known locally as the Cooper Marl), which are characterized as calcareous clayey sands and sandy clays [Camp, 1999]. Soft limestone rock, as defined by a shear-wave velocity of 760 m/s (2500 ft/s) or greater underlie the Cooper Marl at a elevation of approximately – 91 m (–300 ft) Charleston Low Water (CLW) datum.

Figure 1 presents the results of a cone penetration sounding and downhole seismic testing performed along the project alignment. During planning for construction of replacement bridge, it was concluded that for stability reasons, the loose sands and clays would be dredged to the top of the Cooper Marl prior to placement of the rock islands. Considering this, the *in situ* characterization of the strength, unit weight, stiffness, (in terms of shear-wave velocity), and thickness of the Cooper Marl was of primary importance to the seismic stability evaluation.

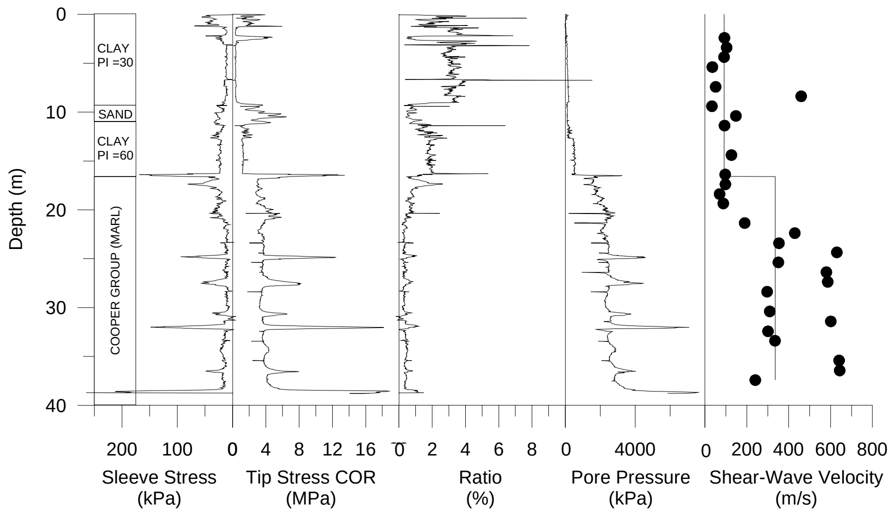

Figure 1. Characteristic Charleston Profile with Clay Overburden.

CONCEPTUAL MODEL

The conceptual model for the rock island is shown in profile in Figure 2. The model parameters for the Cooper Marl were determined from field and laboratory testing in the Charleston region. The rock island material parameters were estimated from published values for anticipated material types Terzaghi, et al., 1996). As a simplification for the seismic stability evaluation, the rock island and channel slopes were conservatively represented in two-dimensions. This simplification is reasonable for the channel slope that will be very long, but may be less representative for the rock island that will have a width at its base of approximately 120 m (400 ft). The evaluation used a maximum dredge elevation of -24 m (–80 ft) Charleston Low Water (CLW), which was intended to yield conservative results on which to based the design length for the main span (and the locations of the rock islands) considering uncertainties in future dredging operations. Both the rock island and channel slope (in the Cooper Marl) are oriented at 2 (horizontal) to 1 (vertical). For modeling purposes, the vertical height of rock island is 18.8 m (61.6 ft) and the vertical height of the channel slope within the Cooper Marl is approximately 9.1 m (30 ft).

EARTHQUAKE MOTIONS

Earthquake motions for the base of the Cooper Marl were developed in the initial engineering for the project for occurrence probabilities of 2%- and 10% in 50 years by scaling the records from the Whittier, Carson Catskill 1987 Whittier Narrows earthquake and Joshua Tree 1992 Landers earthquake, respectively (International Civil Engineering Consults, 2000). Design motions were developed for the three orthogonal directions (vertical and two horizontal directions). This paper is limited to the consideration given to the greater magnitude (**M** of 7.3) earthquake with the lower probability of occurrence. The design earthquake (longitudinal direction) for the 2%/50-year event had a peak ground acceleration of 0.63g and a duration of about 40 seconds.

FLAC ANALYSIS

The dynamic *FLAC* analysis involved: (1) developing a two-dimensional grid (shown in Figure 3) to represent the geometry of the rock island; (2) assigning material behavior parameters, and (3) then applying the external conditions (i.e., the earthquake acceleration) to the base of the *FLAC* grid. The rock island material and Cooper Marl were represented by elasto-plastic soil models. The use of elasto-plastic models is a simplification that was necessary to overcome the difficulty of representing the soil response under two different strain levels – (1) small strains due to induced shear-waves and (2) large strains during slope deformation.

The earthquake motions were applied to the base of the grid (i.e., the bottom of the Cooper Marl) as an acceleration time history. Sensitivity analyses were performed by varying the shear-wave velocity (and the corresponding shear modulus) within the range of measured values. The shear-wave velocity used in the analysis ranged from 365 to 640 m/s (1200 to 2100 ft/s).

RESULTS AND CONCLUSIONS

Using *FLAC*, the results were provided in terms of a deformed grid representing the permanent displacement of the rock island and channel materials. As may be expected, a bulge developed at the toe of the channel slope. The rock island was modestly reoriented with a flatter slope after application of the earthquake time-history. Overall, the maximum earthquake-induced deformation of the *FLAC* grid ranged from 60 to 106 cm (23 to 42 in.). The lower range of shear-wave velocity for the Cooper Marl yield greater displacements. The results indicate that the proposed rock island and channel will perform in an acceptable manner during the design earthquake. The authors conclude that the *FLAC* modeling represented a higher degree of realism and provided realistic results.

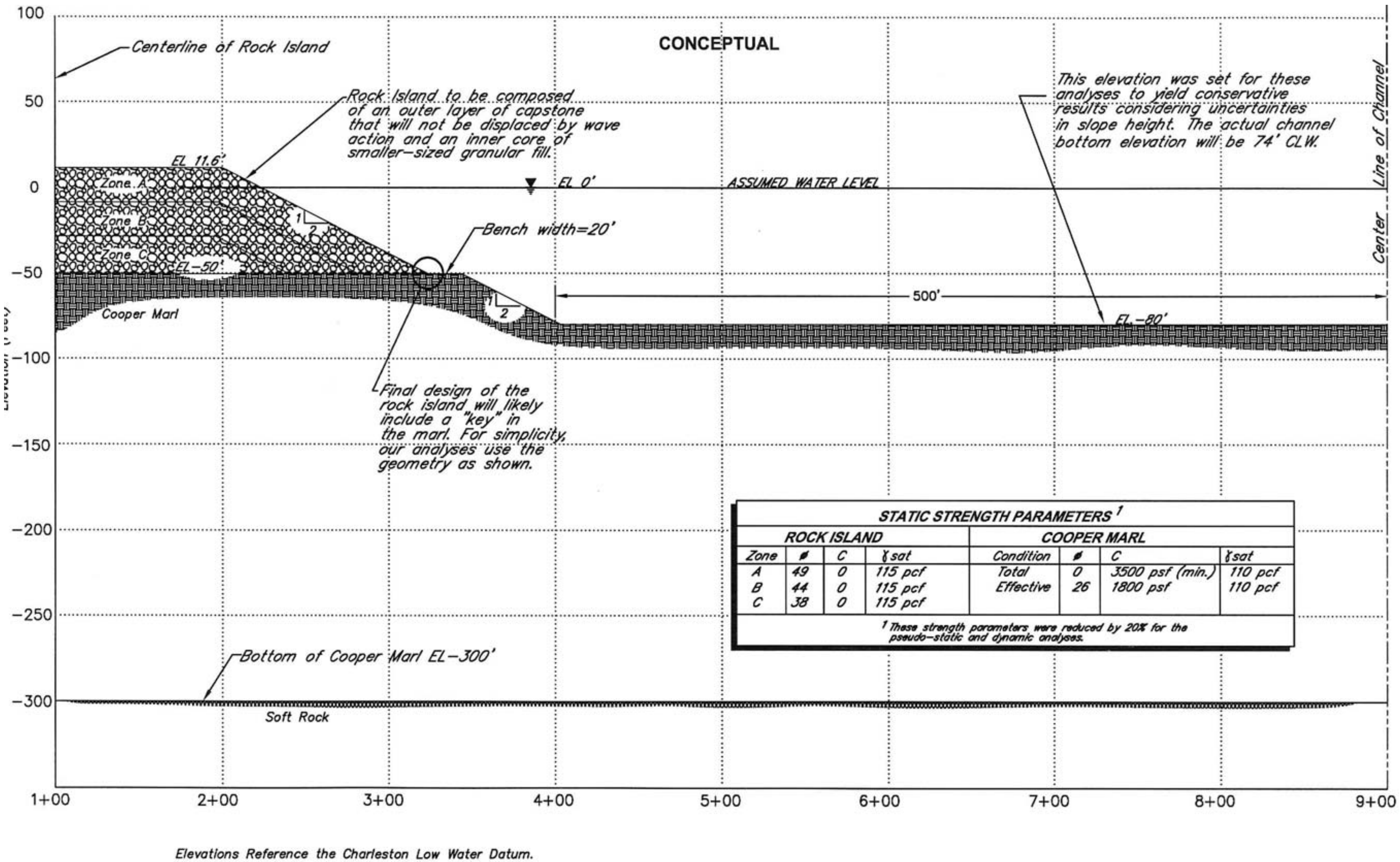

Figure 2. Conceptual Model of Channel and Rock Island

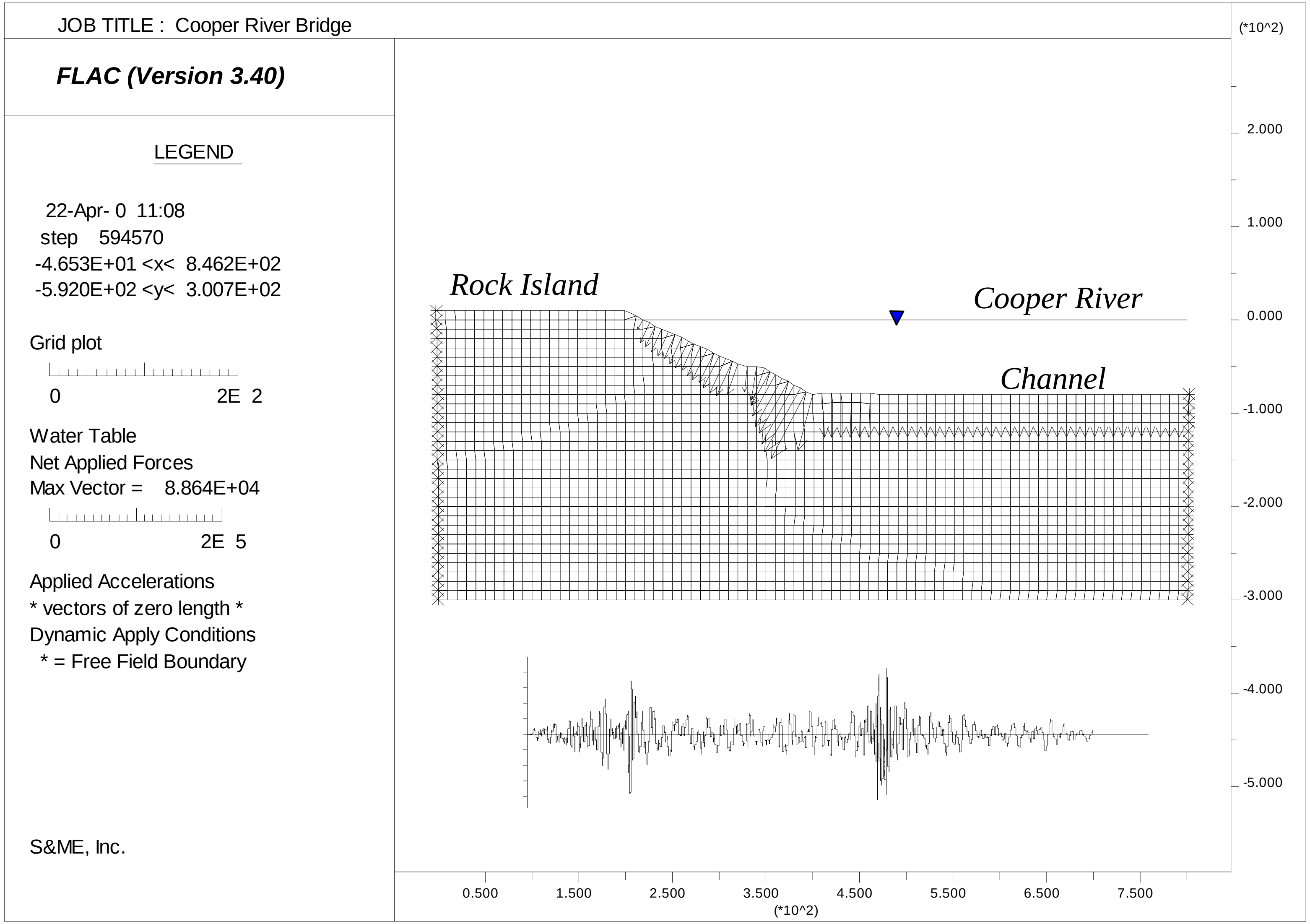

Figure 3: *FLAC* Grid

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