SOIL-STRUCTURE FAILURE MECHANISMS AT TWO BRIDGES IN THE 2016, MUISNE ECUADOR EARTHQUAKE

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ABSTRACT

This paper presents observations from a series of failures of earth backfills behind three single-span bridge abutments in the province of Manabí, Ecuador during the 2016 Mw7.8 Muisne earthquake. The failures had a similar combined pattern of dynamic instability and soil softening due to liquefaction or high seismic strains. Subjected to recorded peak ground accelerations ranging from 0.3 to 1g, the bridge structures seemed to limit soil failure by partially yielding, with failures observed at the abutment wall and/or the bridge deck. This pattern is different from typical failures of retaining walls and embankments that appear primarily in the soil backfill. In the presented cases, the bridge deck acted essentially as a strut, transferring active earth pressures to the opposite riverbank, thus generating a passive earth pressure, relieving soil displacements and preventing geotechnical failure. Documentation of drawings and design details of the bridges, including seismic force-reduction factors assumptions, along with available geotechnical and structural data and observations with actual strong ground motion records are presented. The information is then used to create dynamic models to demonstrate the observed “interrupted soil failure” behavior pattern, with seismic load transferred to the structural elements according to their relative stiffness, with the weaker element suffering the most damage, even reaching full collapse. A resilience-based retrofit approach is proposed, with bridge strengthening and enhancement details to make the bridges able to resist the observed transfer of loads in the 2016 earthquake and anticipate a better behavior in future earthquakes.

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Soil-Structure Failure Mechanisms at Two Bridges in the 2016, Muisne Ecuador Earthquake

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Introduction

Bridge failures after large earthquakes have documented well aspects of slopes, embankments and retaining walls, and abutment failures due to soil-induced deformations. However, little information is available on geotechnical failures behind bridge abutments where the superstructure and deck often seem to provide resistance and ultimately overloading the bridge itself that pays the price. In the 2016 Mw7.8 Muisne earthquake [1,2], several bridges in the province of Manabí exhibited failure mechanism in the earth fill behind abutments, accompanied by structural damage in the bridge deck or abutments, or sometimes in both the deck and the abutments [3, 4, 5]. The two bridge cases presented in this paper and shown on the map of Fig. 1 (Mejía and Cativo) experienced damage to the bearings, each with a different soil-structure failure mechanism and with one of them being near total collapse [4].

![Map of the 2 bridges (Mejía and Jama) presented in this paper.](image)

Most cases of earth failures behind abutments do not appear as classic slope failures, but rather appear as traces of road surface uplifts or depressions, as shown on Fig. 2 at the Mejia Bridge. Such failures and damage in the bridge structure [3, 4, 5] could be analyzed and duplicate the observed behavior as a whole soil-structure system, and not as individual components, as has been done for some of the damaged bridges for reconstruction purposes.

![Surface depression behind the south abutment of the Mejía Bridge (photo by C. Velastegui, Ecuavisa TV).](image)

The Mw7.8 Muisne earthquake was caused by shallow thrust faulting at the plate boundary between the Nazca and South America plates. Nearly 200 people died and damage to the infrastructure was extensive. The cities of Perdernales, Portoviejo, and Jama were among the most
affected, with the Jama Bridge sustaining severe superstructure damage [2,4]. Strong ground motion stations installed by the Geophysical Institute of the National Polytechnic School (RENAC) at the of cities Portoviejo, Pedernales, and Chone (Fig. 1) are in the vicinity of the three bridges. Table 1 shows the characteristics of the stations, along with the recorded Peak Ground Accelerations (PGA) in the horizontal E, N (East, North) and vertical (Z) directions.

Table 1. RENAC strong motion stations near the 3 bridges and recorded PGA values [1,2].

<table>
<thead>
<tr>
<th>City</th>
<th>Bridge Vicinity</th>
<th>RENAC Station</th>
<th>Epic. Dist. (km)</th>
<th>Elev. (m)</th>
<th>PGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portoviejo</td>
<td>Mejía</td>
<td>APO1</td>
<td>167</td>
<td>47</td>
<td>0.32 0.38 0.10</td>
</tr>
<tr>
<td>Manta</td>
<td>Jama</td>
<td>AMNT</td>
<td>171</td>
<td>38</td>
<td>0.41 0.52 0.17</td>
</tr>
<tr>
<td>Pedernales</td>
<td>Jama</td>
<td>APED</td>
<td>36</td>
<td>15</td>
<td>1.41 0.83 0.74</td>
</tr>
<tr>
<td>Chone</td>
<td>Cativo</td>
<td>ACHN</td>
<td>120</td>
<td>18</td>
<td>0.33 0.37 0.17</td>
</tr>
</tbody>
</table>

Case Study 1: Mejia Bridge

General Information

The Mejia Bridge is a single-span twin bridge located 3 km north of Portoviejo, capital of the Manabí province, on the road to Crucita (Fig. 1). The bridge structure is supported by four steel beams with a reinforced concrete slab. The Muisne earthquake caused dramatic embankment near the Mejia Bridge failures as illustrated on Figs. 3 and 4.

Figure 3. South embankment lateral failure at the Mejia Bridge (Photo: Mauricio Espin).

Figure 4. Failure modes of the Mejia Bridge embankments (modified from GEER [2]).
Soil failures occurred along both approach embankments, causing damage to both the north and south reinforced concrete abutments. The south gabion walls sustained extensive damage which have now been repaired. The failure modes of the embankments are shown on Fig. 4, as reported in the GEER (Geotechnical Extreme Events Reconnaissance) Report [2].

**Damage**

The Mejía Bridge sustained both visible and non-obvious earthquake-induced geotechnical and structural damage (Fig. 5). This paper focuses on the latter and its origin, since the visible damage has been studied in other publications [2,4]. The visible damage consisted of a major slope failure of the western side of the south access to the bridge, which discontinued vehicular access (Fig. 5). The sliding movement was towards the river (to the west), likely caused partially by a loosed saturated sand layer at 1.5 m below the foot of the slope, and partially due to dynamic instability of the earth fill itself.

![Figure 5](image1.png)

Figure 5. Mejía Bridge: Aerial view of damage (left) and schematic of the slope failure at the road embankment towards the river.

The slope instability was likely initiated by the weak top of the embankment where the two first traffic lanes were built 20 years ago, with an expansion of another two lanes added 15 years later. To understand this failure and identify the nature and properties of the soil within the failed slope, a test pit was excavated at the toe of the slope (Fig. 6).

![Figure 6](image2.png)

Figure 6. Test pit excavated at the toe of the failed slope at Mejía Bridge
A possible mechanism of failure of the earth fill behind the south abutment, interacting with the bridge structure, was the following [3]: Due to dynamic instability, the earth fill of the south abutment slid towards the river, thus moving the abutment towards the bridge deck, closing the expansion-contraction joint, as shown on Fig. 7. Shear deformation of neoprene bearings occurred at this stage exceeding the shear for the highest deformation expected due to thermal expansion of the bridge.

![Figure 7. Mejía Bridge: Failure in south earth fill and development of passive earth pressure in the opposite abutment (left). South abutment displacement towards the river; south neoprene bearings deformation that reached their capacity at the top (right).](image)

The earth fill continued to move towards the river (Fig. 8), along with the abutment and bridge deck, until closing the opposite expansion-contraction joint, resulting in both joints being closed tight. Shear deformation of neoprene bearings on the opposite abutment also occurred, higher than the highest expected temperature deformation level (Fig. 8).

![Figure 8. Mejía Bridge: North expansion-contraction joint closed and strut effect (left). North neoprene bearings reached lateral deformation capacity at the top (right).](image)

While the earth fill continued moving towards the river, the bridge deck acted as a “strut”, pushing against both abutments. Since the first dynamic soil-structure contact with the abutment was on the same side as the slope failure, the damage was higher in the south abutment, including 12 cm insertion of beams into the top (or back) wall of the south abutment [3], with slight rotation of the south abutment. As the bridge was in contact with both abutments, it prevented the slope failure, transferred load that damaged and weakened the superstructure. In the case of the Mejía Bridge the deck did not sustain significant damage. In other bridges with the similar failure mechanisms, damage occurred in the steel beams, instead of abutment walls. Passive pressure on the north abutment fill was substantial since the top abutment wall had only 1/8th of the inertial load at the bottom of the wall, thus concentrating most of deformations and pressures at the top of the wall, with the bottom developing smaller deformations and lower passive earth pressures. Two types of structural loads with two different abutment wall bearing conditions were identified: (i) a
traditional cantilever (loads left to right on Fig. 9) for active pressures and (ii) a load associated with the strut effect that resembles reactions of a beam on elastic foundation (loads right to left on Fig. 9).

Figure 9. Two types of structural loads at the abutment of the Mejía Bridge.

The distribution of strut forces on the abutment depends on the soil properties, impedance contrast between soil and structure, and design/construction details. Reverse bending moment can occur, which may not be as severe as the punching shear (Fig. 10) which can transfer high loads at the base of deck beams, exceeding their capacity.

Figure 10. Schematic of combined bending moments due to soil pressures and strut effect.

Figure 11. Damage at the opposite (north) abutment wall of the Mejía Bridge.

The opposite (north) abutment also experienced damage with a 5-cm insertion of the steel beam at the top of the wall (Fig. 11). Again, punching shear damage was more prominent at the bottom flange of the steel beams. Additionally, the neoprene bearings of the south abutment were almost destroyed due to the extreme shear distortion, with the neoprene bearings of the north abutments
being affected too. The south abutment bearings were replaced during reconstruction, while neoprene bearings on north abutment remained as they were functional.

**South Access Road Embankment Failure**

The roads of Ecuador that are near the sea shoreline, require embankments to protect them against floods, which are quite frequent. The approach or access to these bridges need to be particularly protected, to allow for water to flow below the bridge. The shorter the bridge is, the higher the embankment should be. South access – west side embankment in Mejia Bridge was the most vulnerable due to a turn in the river, as shown on Fig. 12 a and b.

![Figure 12a. Aerial view of Mejia River, and South Embankment](image1)
![Figure 12b. Sectional View of Mejia River and South Embankment](image2)

The mechanism of lateral failure for earth embankment was the following: Half the embankment slid laterally towards the river. The road was originally a two lane road, and four years ago was transformed into a four lane one. The union of both earth fills was the weakest surface, due to construction procedures, and became part of the primary landslide surface, as shown in Fig.13. Other almost parallel sliding surfaces appeared during the first landslide.

![Figure 13 Primary and Secondary Landslides](image3)

The sliding pattern shown in Figure 13 appeared in different places of the embankment, at a different scale, and in other bridge accesses and road embankments in Manabí.

**Case Study 2: Jama Bridge**

**General Information**

The Jama Bridge is located near the town of Jama, on the road from San Vicente to Pedernales, which is part of the touristic Spondylus route (Fig. 14). The configuration of the bridge has one span 64 m and consists of a double Acrow panel bridge, for two vehicular lanes and two pedestrian walks.
Damage at Jama Bridge

There was important structural damage on the East access of Jama Bridge (Figure 15a, b), but there was no visible nor hidden damage on the West Access. The origin of the structural damage was a restricted landslide of the earth fill of the west abutment, towards the river [3], with a similar geotechnical mechanism to the one observed in Mejía Bridge (Fig. 10). Damage consisted of the destruction of part of the supporting panels in the East Access [3], putting the bridge in serious risk of instability [4].

The Mechanism of Failure in Jama Bridge

The failure mechanism for a landslide interacting with the bridge steel structure, was the following:

- The earth fill of the east abutment slid towards the river, thus moving the abutment towards the bridge deck panels, and closing the expansion – contraction joint.
- Important damage is seen in the metal bearings and east support panels.
- The earth fill continued moving towards the river, with the abutment and the bridge deck, until closing the opposite expansion – contraction joint.
- While the earth fill continued moving, the bridge deck acted as a strut, pushing against both abutments. Since the first dynamic contact was with the abutment on the same side of the landslide, the biggest damage was concentrated in the eastern panels (Fig. 16 a), including 30 cm insertion of the abutment into the bridge superstructure, support panels weakening (Fig. 16b).
The presence of the bridge deck, in contact with both abutments stopped the landslide movement, but damage had already occurred in the structure. Most of the damage occurred in the steel bridge, but the concrete abutment was also damaged. No significant damage was detected in the opposite side of the bridge superstructure. Relocation of the bridge, avoiding the use of the eastern panels, and building a new bridge was selected as the solution.

The Level of Damage in Jama Bridge

Damage in Jama Bridge was extensive; this was the only one of the two bridges analyzed that was perilously close to collapse. This is because damage occurred in supporting elements. Acrow panelized bridges are modular, temporary structures, designed to carry gravity loads, and some wind loads, but no seismic load. A daily monitoring procedure was implemented until reconstruction could begin. The only advantage of this type of bridge under seismic loading is that bridges are relatively light, and inertial forces are generally light too.

The two seismic problems with Jama Bridge, under the Muisne earthquake were:

- Inertial forces were produced by the bridge deck mass, but also by the earth fills, and abutments, so inertial forces affecting the steel bridge were 2 to 3 times higher than expected (around 200 Tons in east abutment).
- Due to the mechanism of failure, which involved earth fill failure (movement), high seismic forces coming from earth fills were not distributed through the bridge mass. Most of them were concentrated loads, acting in one or two node points, thus causing extremely high bending moments in one deck beam, provoking horizontal deformations (Fig. 16 a).

Conclusions

The 2016 Muisne earthquake taught that many bridges, particularly one span bridges, can suffer great damage due to the strut effect, which means that adjustments must be made to conventional bridge design methodologies.

During a major earthquake, bridge abutment backfills can fail and slide towards the river. The effects vary according to the special conditions of each bridge and specific soil properties. When large seismic accelerations are present, it is possible to have landslides in abutment backfills that can be arrested by the bridge structure acting against the abutments. In these cases, the bridge usually pays the price for braking the soil, measured in terms of structural damage.
Sliding of soil fill pushes the abutment until it is in contact with the bridge deck, and continues moving until contact is made at the opposite riverbank abutment, creating a powerful landslide braking process.

The bridge superstructure and deck act like a strut between the two abutments. The strut effect produces stresses in the upper part of abutments, and at the ends of the bridge deck, that are generally not analyzed during design. Forces generated in the contact points are extremely high, and they generally provoke damage at the beam ends and at the upper part of the abutment. In some cases, the destruction of such elements can put a bridge’s stability at risk.

Strut effect is not the problem by itself; quite the opposite. After analyzing bridges that experienced this phenomenon, global abutment failure had been avoided, and a structural collapse prevented.

The problem that needs to be solved is that neither the bridge deck (particularly beams), nor the abutments (top wall) are designed to resist, restrained earth fill failures, behind abutments.

The closest real model is probably to estimate forces involved in the strut effect, consisting of consideration of a simple support at the gravity center of the bridge deck and the static equivalent to dynamic earth pressure.

To diminish the punching shear effect from steel beams on a reinforced concrete top wall, a special welded steel box detail should be used in traditional “I” steel beam bridges.

Acknowledgments

The authors acknowledge the collaboration and exchange of information with the US team of the Geotechnical Extreme Events Reconnaissance (GEER) Association funded by the National Science Foundation (NSF) and the Applied Technology Council (ATC), as listed in [2].

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