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Reef slope failure in the northeastern corner of Malè, Maldives

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Abstract. This study examines reef-slope failure that occurred on the northeastern corner of Malè Island on the 6th of February, 2002. Malè, the capital of the Maldives, has an area of 1.5 m^2 and a population of 130,000. The failed slope area was mapped and systematically investigated by comparing aerial photographs and satellite images from 1969 to 2007. The investigation shows that the reef-flat caprock consists of 2 to 3 m of slightly cemented coral and rubble overlying 4 to 6 m of weakly cemented, highly erodible coral sand and rubble located 10 to 30 m down the 30° slope. The failure may have occurred as a single event during which an integral rock mass disintegrated into individual blocks. Radiocarbon dating of the rock samples indicates rapid vertical reef growth, but horizontal progression played a more important role in reef formation. Aerial photographs and satellite images show four additional reef-failure areas on the northern side concentrated in areas of heavy urban-development overburden and continuous vibration from industrial activities. Due to reef failure, the strongly cemented caprock was removed, and the weakly cemented highly erodible layer was exposed to further erosion. The eroded parts are expected to fall into the atoll lagoon and cause further retreat of the reef edge. Proper remedial action must be taken to maintain overall stability and ground-bearing capacity of the island.

Keywords: Reef; slope failure; Malè; Maldives

Introduction

Malè is the capital city of the Maldives with an area of 1.5 m^2 and a population of 130,000 people. The island, located within and along the south eastern edge of a large north/south-trending atoll, has been reclaimed to the maximum extent possible, and heavy tetra-pod breakwaters have been constructed on the reef flat around the island. Heavy weight from new constructions, buildings, and industrial activity burdens the reclaimed area (Fig. 1).

Submarine reef slope failure triggered 19 days after a barge collision incident with an existing solid jetty that had been built on the reef flat in the northeastern corner of Malè in 1999. Two years after jetty completion and onset of industrial construction, the slope in that area failed in February 2002. Blocks of reef flat fell into the atoll lagoon, creating a number of new cracks that developed in various parts of the reef flat and slope. Some of these cracks extend 20 to 30 m into the slope.

Generally, slope failure was initiated by stress construction at the edge of the slope and was followed by cracking. Major factors that govern slope stability are slope angle and material properties, such as cohesion and the angle of friction. Typically, slopes with an angle of 20 to 30° and low cohesion are vulnerable to failure. In this case, however, the slope angle was around 10 to 15° and the material consisted of very cohesive and strongly consolidated 1- to 2-m thick reefal limestone. Thus, it is suspected that slope failure was affected by stresses induced by the excessive weight put on the island subsurface.

Study Methods

Investigation and systematic monitoring of collapsed reef area on the northeastern corner of Malè has been ongoing since 2004. The geologic structure of the collapsed area was mapped and systematically classified following general procedures in geotechnical engineering.

Cubes of collapsed blocks were measured and depths were recorded along three profiles that emanate from the edge of the reef flat and follow the reef slope onto the atoll lagoon floor to a depth of 45 to 50 m. The intra-reef structure was observed at the collapse scarp from the reef surface to –35 m. Rock samples collected from various depths of the collapsed area were dated using the radiocarbon method. To monitor the progress of cracks in the collapsed area, two pegs were installed on both sides of the crack and tightly connected with fishing lines. Aerial photographs and satellite images of Malè reef were taken in 2007 and were compared with the previous images taken in 1969, 1996, and 1999.

Results and Discussion

The reef-flat caprock consists of 2- to 3-m-thick slightly cemented coral rock and rubble. Beneath the caprock is a 4- to 6-m-thick weakly cemented highly erodible mixture of coral sand and coral rubble. Farther down (10-30 m), the 30° slope has been built up by loose gravel and sand.

Figure 1: A Digital Globe® satellite image of Malè taken in 2007, top, aerial photograph of north eastern corner of Malè taken in 1999 at the bottom, showing the solid jetty prior to the collapse.

The block field lies on the atoll lagoon floor at a depth of 30 to 40 m. The failure might have occurred as a single event, and as the rock mass was in motion, the mass disintegrated into individual blocks to form the block field. Total volume of the rockslide is estimated to be several thousand cubic meters (Figs. 2 & 3).

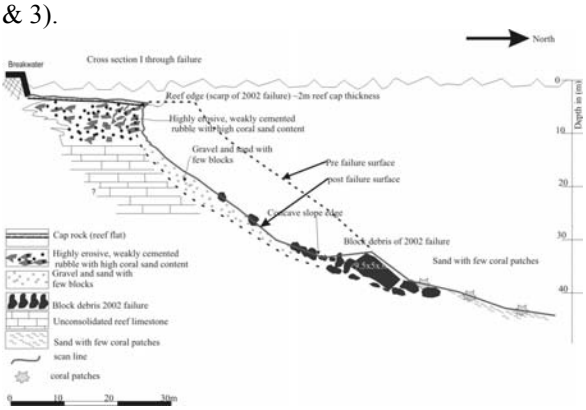

Figure 2: Cross section of failure area.

The monitoring pegs installed in 2004 have been broken. In addition, new cracks to the east of the collapsed area were observed in 2007. The cracked blocks appear to be unstable and continuously and slowly moving (ERC 2007).

Both the eastern and western scarps as well as the collapsed part of the reef are exposed to strong currents and wave action. Thus, the weak layer in the reef is continuously being eroded and is undercutting the reef edge. A freshly fallen reef block was found during the survey.

The collapsed scarp shows that the reef surface is consolidated at the top 2 to 3 m by the accretion of tabular, massive, and stubby branching corals. The sedimentary structure changes gradually to the coral casts near the bottom of the scarp (Fig. 4).

Radiocarbon dating of rock samples shows the oldest material occurs at the 20-m depth, and the youngest is at the top of the reef. This indicates that, even with the rapid growth of the vertical reef section, the horizontal progression of the reef played a more vital role in reef formation.

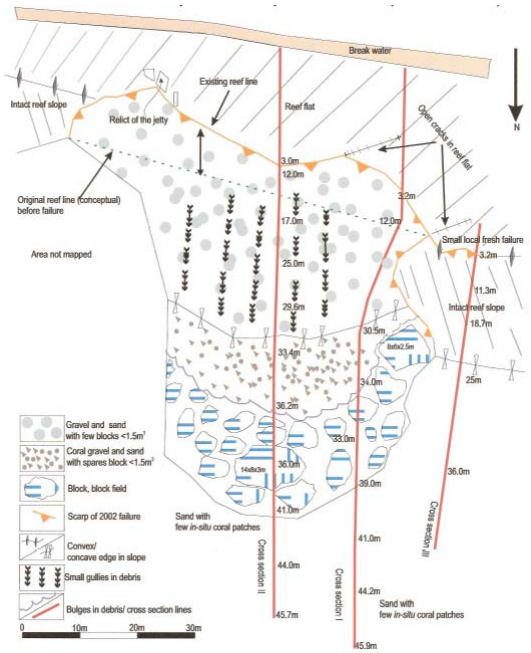

Figure 3: Plan view of failure area.

The reef surrounding Malè Island is continuous, and no collapsed area is found in aerial photographs taken in 1969 (Fig. 5). The reef area of the northeastern corner had not failed, whereas the area on the northwestern part had failed. Furthermore, satellite images taken in 2007 showed failure at four circled areas (Fig. 6). Those failures are concentrated in the areas of heavy construction and continuous industrial vibration. Although these areas are clearly visible in the photos, they need to be validated through field observations.

The study found that the geomechanical cause of the slide is a combined weakly cemented layer of coral sand and rubble several meters thick and urban construction. Similar subsurface conditions were determined by core drilling at Rasdhoo atoll (Gischler et al. 2008).

It is evident that the reef scarp, including the weak layer, is exposed to prevailing current and wave action and hence to active scouring beneath the consolidated layer. It is expected that parts of the reef will continue to fall into the atoll lagoon, leading to additional backward retreat of the reef edge toward the breakwater.

Further investigation is required to determine the lateral extent of the weak layer. Such an investigation is crucial prior to taking any remedial measure to stabilize the unstable reef slope. Further analysis of slope stability is also needed (Damjanac 1999).

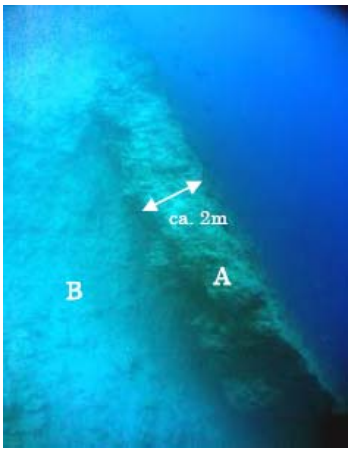

Figure 4: Scarp of the collapsed area showing the composition of the Malè house reef: A is the consolidated hard layer and B is the unconsolidated reef framework.

Figure 5: Aerial photograph taken in 1969.

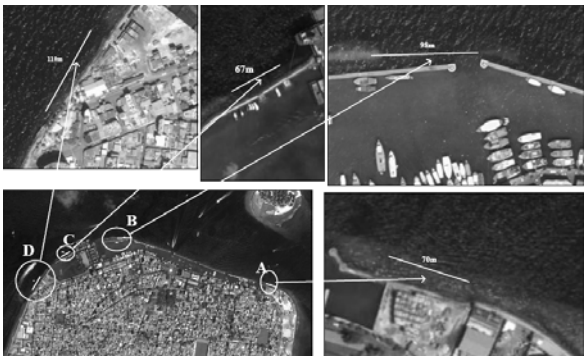

Figure 6: Magnified view of satellite image (2007) showing the failed areas on the northern reef of Malè.

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