Understanding the future of the tsunami-affected coast in a tectonically active coastal region

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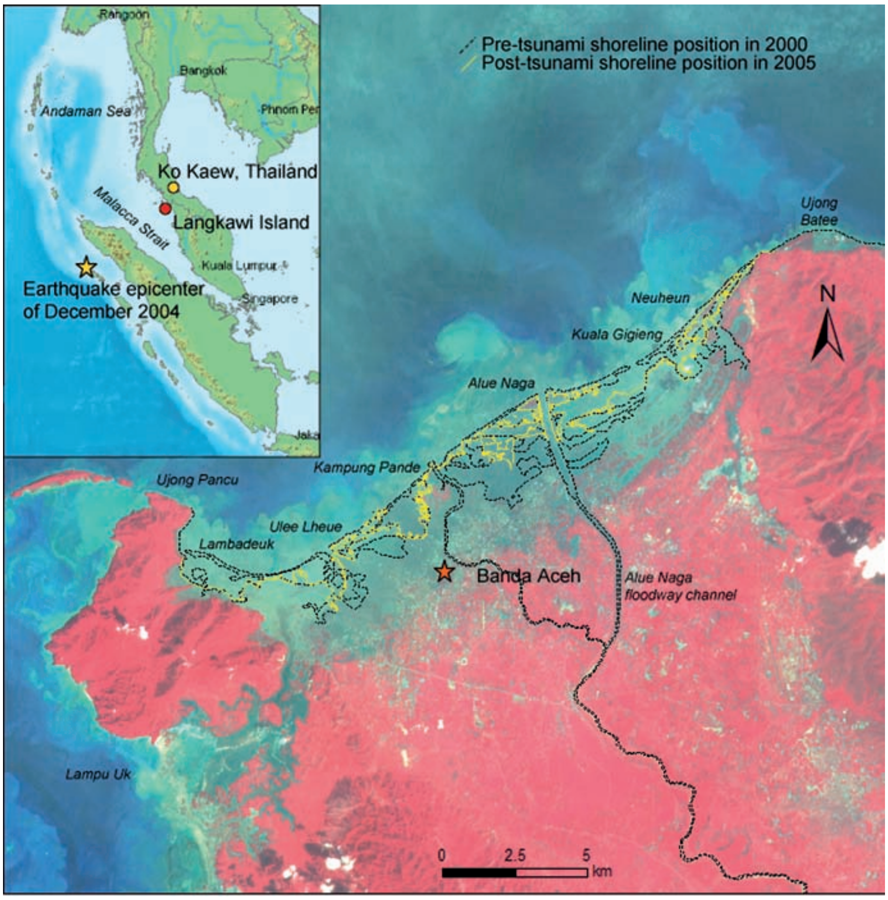
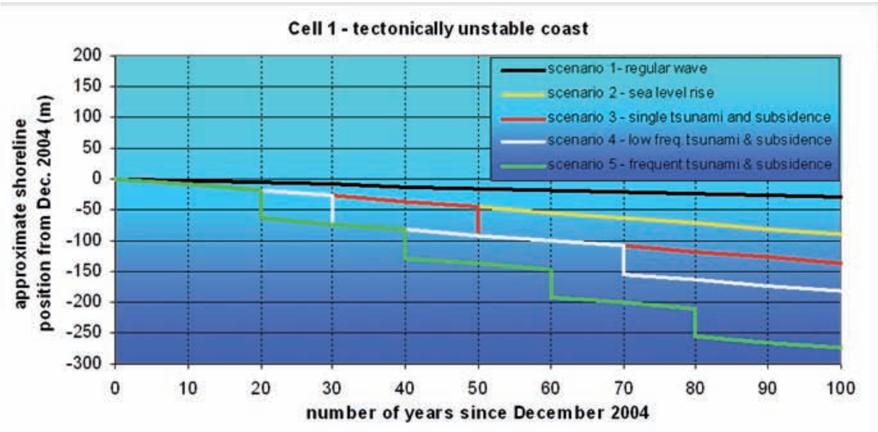
In the early days after the large scale earthquake and tsunami hit Banda Aceh on 26 December 2004, a coastal area on the tip of Sumatra Island, Indonesia, scientists came from all over the world to this coast to witness and investigate the scale of damage that these rare disaster have caused to this broad low-lying coastal area. Many of them researched the direct impact due to the earthquake and tsunami, but mostly without further investigate the extent of the changes of the coastal morphology. A lack of comprehensive study about the coast before the tsunami event was mainly the problem. Without the knowledge of how much the coast has changed the new state of the coastal morphology cannot be determined, thus, forecast of the coastal development may lead to bias result.

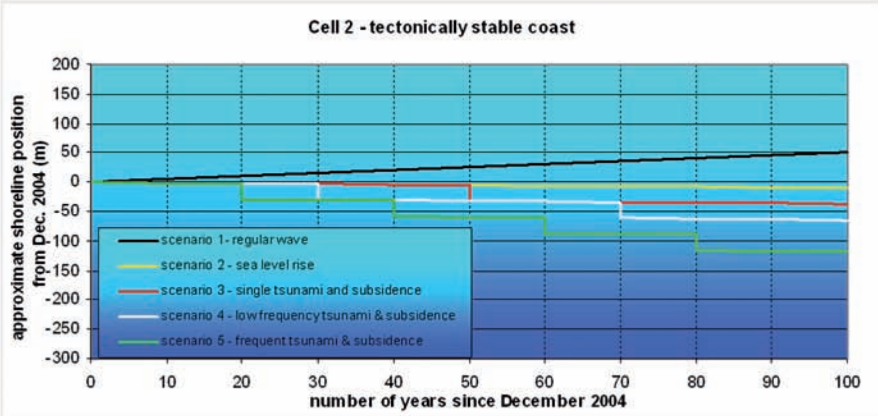
In this research, a thorough geomorphological investigation was applied to analyse the morphological response; the extent of the damage, and development of the Banda Aceh coast before and after the tsunami. The main objective was to increase the understanding of the future development of a coastal system that is prone to the large-scale natural interventions of tectonic land subsidence and tsunami.

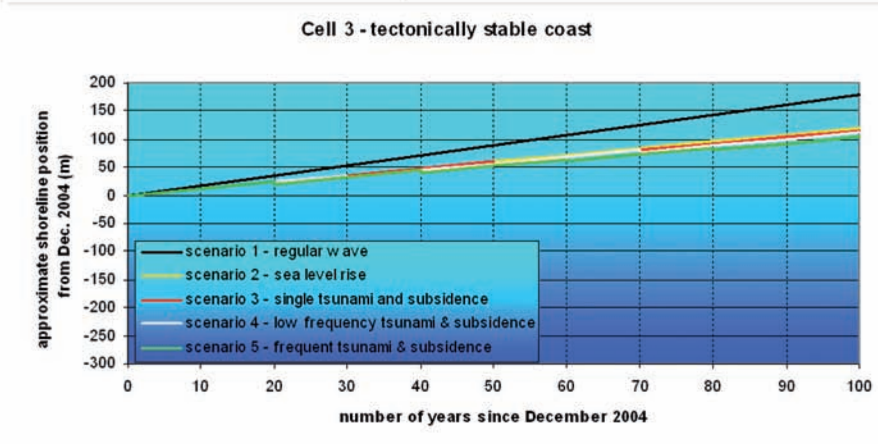
Based on the fact that little was known about the forcing factors involved in the geomorphologic history of the Banda Aceh coastal plain, the objective was more specific to fill in the gap of knowledge about this study area by investigating the forcing factors and geomorphic settings of the coast in general, as well as the magnitude and frequency of tsunami and land subsidence occurrences that were involved in shaping the morphology of this specific coastal area in the history. This information is subsequently used to set some scenarios of morphological development in future.

The research in this thesis rested on the notion that older morphological units can be identified to some extent in the present coastal morphology. Each older morphological unit provides a boundary for the more recent units and therefore co-determines the more recent morphological developments. We argue that in a short-term, a coastal development constitutes









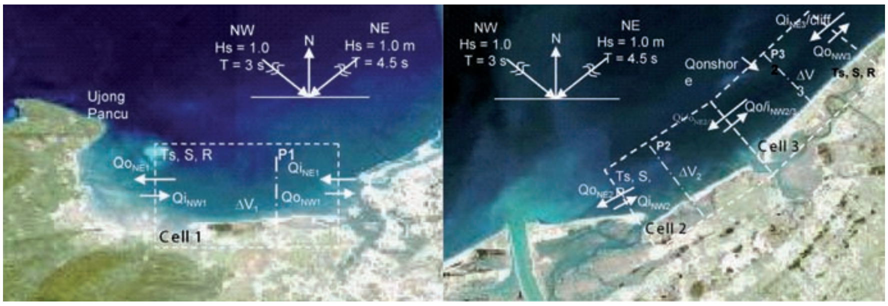
the foreshore development which asymptotically reached a short-term equilibrium. Moreover, the sediment characteristics and availability determine the trend of morphological development of the coast after the intermittent event such as a tsunami and a land subsidence.

The longer the time scale being considered, the more forcing factors with different frequencies are involved in the coastal morphological development. In a tectonically active region, sudden or rapid land uplift or subsidence resulting from the vertical tectonic movements and the resulting tsunamis are considered as the intermittent forcing factors involved in a hundred-year time scale. At the same time, littoral sediment transport induced by wave actions (continuous forcing factors) plays an important role for the development of the coastal morphology. Shoreline position and orientation are two important parameters to take into account in determining the state of a coast; whether it is an eroding or an accreting coast. As a result of the sudden impact of a tsunami or a land subsidence, the shoreline position and orientation as well as the shoreface morphology may change considerably. These changes lead to a new coastal state and determine the subsequent morphological development.

This thesis took the explorative methodologies and emerged the time-scale-related issues on the coastal morphological processes related to the earthquakes and the related tsunami and land subsidence. The flow of the research was driven by a wide span of geomorphological interpretation, field observations, spatial data analysis from satellite images, topographic and bathymetric maps, analysis of forcing factors magnitudes and frequencies as well as sediment budget analysis of the littoral transport. The integration of various approaches providing available data sets was done to achieve the essential knowledge about the study area by filling in the gaps of knowledge both on the geomorphic settings and the forcing factors involved in the morphological development.

Banda Aceh coast is a sand-poor environment contains only a thin layer of loose sand on top of a consolidated Holocene prograding delta. The earthquake and tsunami of 26 December 2004 also affected the morphological units that have been established in the Holocene period. The seawater inundated to the coastal plain as far inland as the shoreline position of 0.6 ky BP, during which a similar magnitude of tsunami confirmed to have occurred. The responses of shoreface profiles to the tsunami waves were different from one profile to another due to different geomorphic settings. This shows that such huge tsunami and the accompanying land subsidence effect occurred instantaneously, but it led to changes in morphology comparable to changes that normally occur on the time scale of century to millennia.

Two coasts of different geomorphic settings and sediment characteristics were investigated for the short-term analysis; i.e. Ulee Lheue, on the northwest coast and Lampu Uk on the west coast of Banda Aceh. In the early days after the tsunami, both coasts experienced foreshore morphological adjustment, revealed by the smoothening shoreline undulations and foreshore slope. After 6 months they showed opposite trend from their pre-tsunami positions. Ulee Lheue, on the northwest coast, experienced ongoing erosion of about 15% of the total sediment loss due to the tsunami. The ongoing shoreline retreat at Ulee Lheue after the December 2004 tsunami suggests that the extent of coastal erosion and the lack of sediment supply in the littoral zone after the tsunami could not keep the pace with the sudden change of coastal elevation due to the land subsidence. As a result, the shoreline was retreating even further. At Lampu Uk, on the west coast, 60% of sediment loss due to the tsunami gained back to the coast after 6 months, and a remarkable pile of sand was accumulated on the backshore after two years since the tsunami. The width and the slope gradient of the shoreface and inner shelf as well as the sediment availability and characteristics in front of each coast control this contrasting behaviour. The amount of re-distributed sediment back to the shore may have exceeded the magnitude of the elevation difference caused by the land subsidence.



Both earthquakes and tsunamis have remarkable impacts on the coastal morphology and its future development. The long-term trend of coastal development may be interrupted, which also means that a long-term equilibrium condition may not exist. At an accreting and tectonically stable coast (e.g. Kuala Gigieng) the rate of advancing shoreline is halted due to the expected effect of sea-level rise, and can be further halted by the effect of erosion by the intermittent tsunami events. On the other hand, at an eroding and tectonically unstable coast (e.g. Lambadeuk), the sea-level rise increases the rate of shoreline retreat, and can further be exacerbated by the effect of land subsidence which may cause an irreversible shoreline retreat, especially in the sand-poor coastal environment.

This research suggests that the damage caused by the probable recurrence of tsunami and land subsidence events to the coastal morphology within a century can be an order of magnitude greater than the effect of the well-known sea-level rise due to global climate change, which is often considered important in modern coastal management practices. In a time scale of a century, tsunami and land subsidence events due to tectonic activities are not unprecedented. More frequent but smaller magnitude tsunami and subsidence may occur; i.e. once every 20 to 30 years. Management of such coastal area in future should consider such magnitudes of intermittent forcing factors in the coastal morphological development analysis. In this way, we built a sound coastal morphological foundation to inform important aspects necessary to be taken into account in the coastal engineering and management practices for the tectonically active coastal region.

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