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Abstract

The Salt Range of Punjab Province, Pakistan, lies in the shadow of the Kashmir mountains that embody the convergence of the Indo-Australian and Eurasian Plates. Tectonic stress accumulations from this convergence can trigger events as large as M8 in the heart of the plate boundary. The 2005 M7.6 Kashmir earthquake is the largest event in the region characterized with modern instrumentation. Historical records suggest that a larger 1555 M8 earthquake ruptured a portion of the plate boundary adjacent to the southern limit of the 2005 M7.6 rupture zone. Earthquake occurrence is limited to smaller $<$M6 events in the diffuse margins of the boundary, where the Salt Range is located. The Salt Range includes bedded salt layers having thicknesses of up to 2000 m (6562 ft) and hosts the Khewra mine, the second largest salt mine in the world. Pakistan is a developing country with increasing needs for sustainable energy security. Because the Salt Range is adjacent to major highways and infrastructure, the creation of underground salt caverns could provide a reliable and secure solution for the energy needs of an underserved population. The proposed sites for new Liquefied Petroleum Gas (LPG) storage caverns in the eastern Salt Range target bedded salt layers with depths spanning 300-500 m (984-1640 ft). These sites are roughly centered between major population centers of Islamabad and Lahore. The engineering requirements for the creation and operation of such caverns are well-established. However, the proximity of the proposed sites to a major plate boundary presents a new requirement to understand the hazards of potential earthquakes on salt caverns. We investigate these hazards from three perspectives. First, we calculate the shear stresses and pressure changes at the proposed cavern sites caused by the modern 2005 M7.6 earthquake. Second, we examine similar predictions caused by the historical 1555 M8 earthquake, which occurred in what is currently a seismic gap along the plate boundary. This seismic gap is cause for concern, as it may represent the location of an upcoming large event. Third, we examine probabilities of stress and pressure changes with Monte Carlo sampling of local M6 scenarios local to the proposed sites. Both the 2005 M7.6 and 1555 M8 earthquake scenarios generated tremendous near-field changes in shear stress and pressure. However, the magnitudes of these predictions quickly diminish with distance and are insignificant at the proposed cavern locations. Based on historic seismicity data, the proposed cavern sites are sufficiently far ($>$150 km, 93 mi) from the heart of the plate boundary to be directly impacted by large $>$M6 events. We conduct 500,000 Monte Carlo simulations of M6 earthquakes to evaluate impacts from smaller events that occur in the diffuse margins of the plate boundary local to the proposed sites. Results suggest that an M6 event within about 10 km (6 mi) of the proposed sites could generate significant shear stress or changes in pressure. However, the probability of such an event is $<$1%. Proactive engineering, such as adjusted safety factors and on-site pressure relief and injection capabilities, could mitigate the risk from low probability, but potentially impactful, seismic events.

Keywords: cavern pressure, earthquake hazards, liquefied petroleum gas, LPG storage safety factor, Salt Range, salt caverns, Pakistan, underground storage