Analysis of Surface Deformation Patterns Affecting Taiwan's High-Speed Rail System near Tuku, Yunlin County, Taiwan

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Background

West-central Taiwan continues to experience excessive land subsidence due to the overexploitation (3.3 billion cubic meters annually) of the Choshui River alluvial aquifer system in support of its extensive agriculture and aquaculture economies in Chunghwa and Yunlin Counties (Lee, Yu et al. 2018). Taiwan's high speed rail (HSR) system extends north-south through one of the country's most severe land subsidence bowls near Tuku in Yunlin County, south of the Choshui River (Fig 1). The pillars near Tuku that support the HSR reside along the eastern flank of the most severe subsidence bowl in the region, causing the pillars to subside, move laterally westward and tilt eastward (Taiwan HSR, personal commun, 2020). The eastward tilt is contrary to logical thinking and a perplexing problem when subsidence is viewed as a one-dimensional problem. This research shows that when viewed in a three-dimensional framework, the motions occurring along the HSR near Tuku can be readily explained through examination of the surface motions from the GNSS network, understanding the influence of the aquifer-system boundary conditions and careful analysis of results from an E-W plane-strain aquifer flow and deformation model of the individual aquitards and aquifers encountered vertically by the foundation of the pillars.

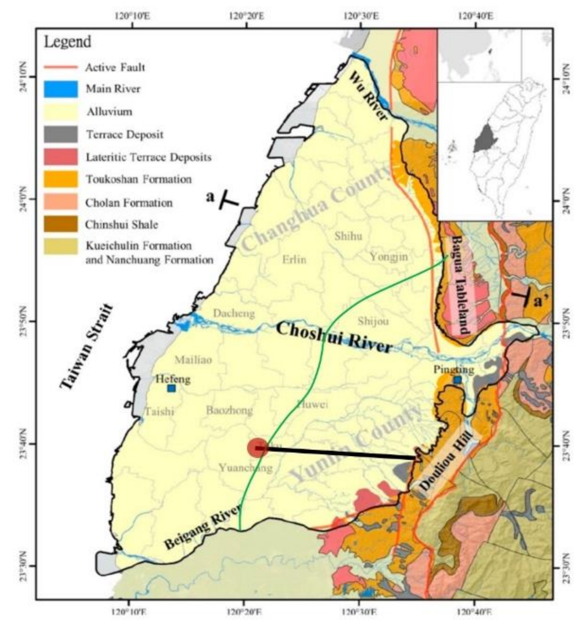

Figure 1 Location of study area in Yunlin County. Black line shows extent of plane-strain numerical model. Green line is the high-speed rail (HSR) system and red circle is the subsidence bowl impacting the HSR.

Study area

Chunghwa and Yunlin counties in west-central Taiwan cover 1,800 km2 with the Choshui river bisecting the counties and flowing westward from the highlands in the east (100 m amsl) to the coast bordering the Taiwan Strait (Fig 1) (Tatas, Chu et al. 2022). The aquifer system is composed of sands, silts and clays eroded from the sedimentary and metamorphic rocks along the eastern boundary of the aquifer system (Fig 1). The uppermost 200m of aquifer system in the study are is composed of three aquifers (ranging in thickness from 42m to 95m in the mid fan but decreasing westward) and two intervening aquitards that vary in thickness from zero along the eastern margin to more than 100m in thickness along the coast where the clays dominate (Fig 2) (Ali, Chu et al. 2021). The major subsidence bowl near Tuku in Yunlin county is in the mid fan part of the aquifer system. Aquifer two (AQ2) is the primary producing unit leading to most of the land subsidence in the area and occurs within the uppermost 200m of the system (Chu, Ali et al. 2021). The distance from the pumping center in Tuku to the eastern boundary is approximately 25 km.

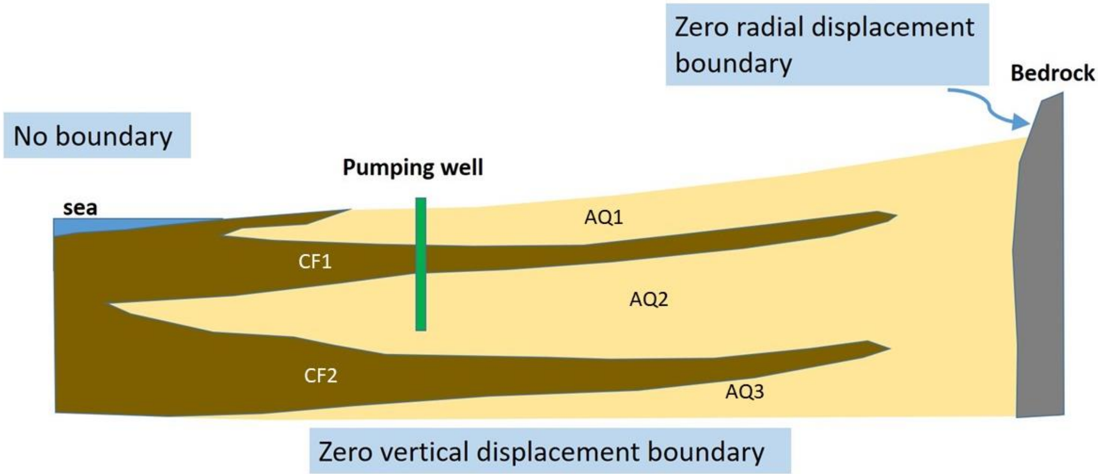

Figure 2 Conceptual model along east-west section near Tuku (black line in Fig 1) showing aquifers (AQ) and aquitards (CF) in the uppermost 200 m of the system. The numerical model extends from the pumping well to the eastern bedrock boundary (25km).

Methods

Taiwan has one of the most widespread GNSS networks in the world (Hung, Hwang et al. 2010). However, all motions on Taiwan are typically measured relative to a station in Penghu, an island off the coast in the Taiwan Strait. This results in the general motion of mainland Taiwan to move westward or northwestward, particularly those stations situated within the study area due to the overall plate motion on which Taiwan resides. However, because the aquifer is free to move from pumping-induced deformation relative to bedrock and plate motion, the GUKN station within the bedrock just east of the Choshui alluvial aquifer system is chosen as the reference frame for this investigation. This changes the direction of motions within the aquifer system to an eastward orientation; that is, toward to only fixed boundary condition within the aquifer system. This eastward motion is attributed to extensive groundwater pumping in the mid fan region (near Tuku in the study area).

A two-dimensional plane strain Biot model (Hsieh 1996) was constructed to simulate groundwater flow and vertical and horizontal aquifer deformation in the region from the pumping center near Tuku to the eastern fixed hardrock boundary (no radial displacement, Fig 2), a distance of about 25 km. The model is free to subside vertically on the lateral boundaries. The eastern lateral boundary has an outward flux in the zone representing aquifer two but this boundary is free to move horizontally and vertically. The bottom boundary is allowed to freely move horizontally but is fixed vertically. The total thickness of the model is 200 m, representing the uppermost sediments and active zone of pumping. The model simulates flow and deformation in a three aquifer—two aquitard model using hydraulic and poromechanical properties obtained from pumping tests, drilling logs, laboratory testing and previous investigations.

Results

Numerical modeling results support the GNSS surface deformations when using GUKN as the reference frame. When excessive groundwater pumping occurs in the mid-fan region, the fixed eastern boundary causes the continuous deformable aquifer system to be pulled toward it (Fig 3). Furthermore, greater surface deformation occurs toward the east and is dampened with depth, particularly through the clay confining layers, which, according to numerical results from the Biot model, tends to impede horizontal motion causing a shearing effect (Fig 4). Horizontal deformation through each aquifer is constant at a particular location with the uppermost aquifer experiencing the greatest eastward deformation and the third aquifer (150-200m depth) experiencing the least. This pattern explains why the pillars are tilting toward the east and not toward the west, which would be the case if a draping effect were dominating the deformation. Pillar foundations extend 60 m into the aquifer system; deep enough to experience the lessening eastward horizontal motion with depth (Fig 5). In addition, the pillars near the Tuku subsidence bowl are actually moving eastward at a lower rate than the pillars north and south of the subsidence bowl. This slower rate is hypothesized to be due to the larger thickness of clays in the vicinity of the subsidence bowl and extending eastward. This hypothesis is supported by the drilling logs when the pillars were installed.

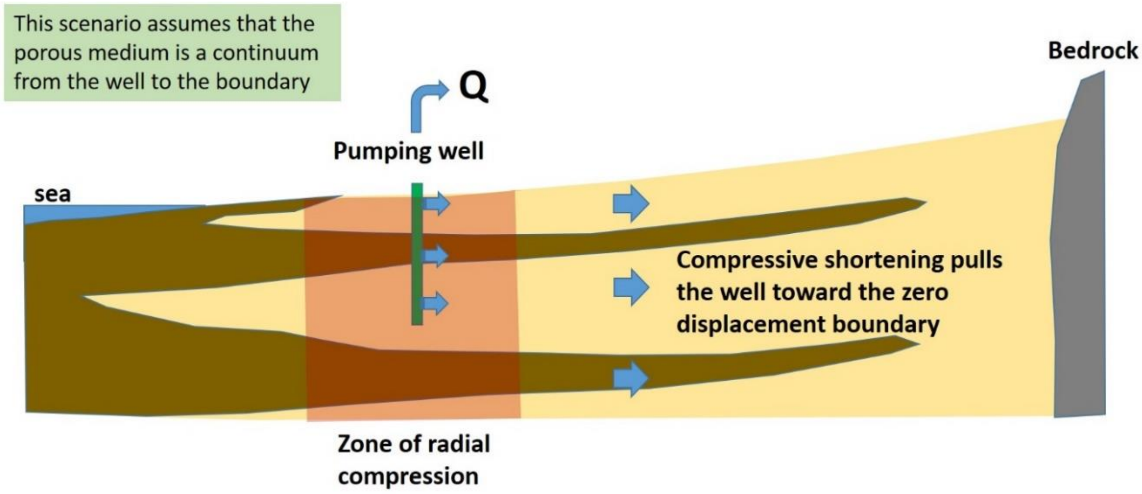

Figure 3 Although a region of radial compression occurs in the vicinity of the subsidence bowl, the overall motion of the aquifer is drawn toward the eastern boundary because the aquifer behaves as a continuum.

These findings reveal the vital role of fixed boundary conditions in large-scale deformation modelling and the role that excessive groundwater pumping and aquifer heterogeneity play in influencing both surface and subsurface three-dimensional deformation patterns. This understanding is important for managing and mitigating the deleterious effects of groundwater pumping on Taiwan's HSR system.

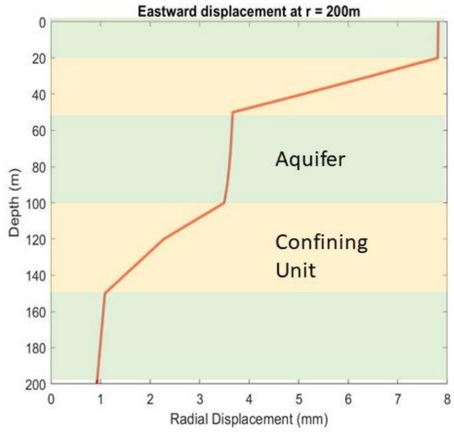

Figure 4 Numerical results showing that clay units dampen horizontal motion causing a shearing that causes a decrease in eastward motion with depth

Conclusions

Excessive groundwater exploitation in Chunghwa and Yunlin counties in west-central Taiwan has led to continuous and widespread land subsidence. An extensive GNSS network reveals that surface deformations from pumping are eastward toward the "fixed" mountains. Taiwan's HSR runs north-south along the flank of Taiwan's largest subsidence bowl. Numerical modeling reveals that eastward motion is dampened with depth through the topmost three aquifers and leads to an eastward tilt of the pillars near the subsidence bowl.

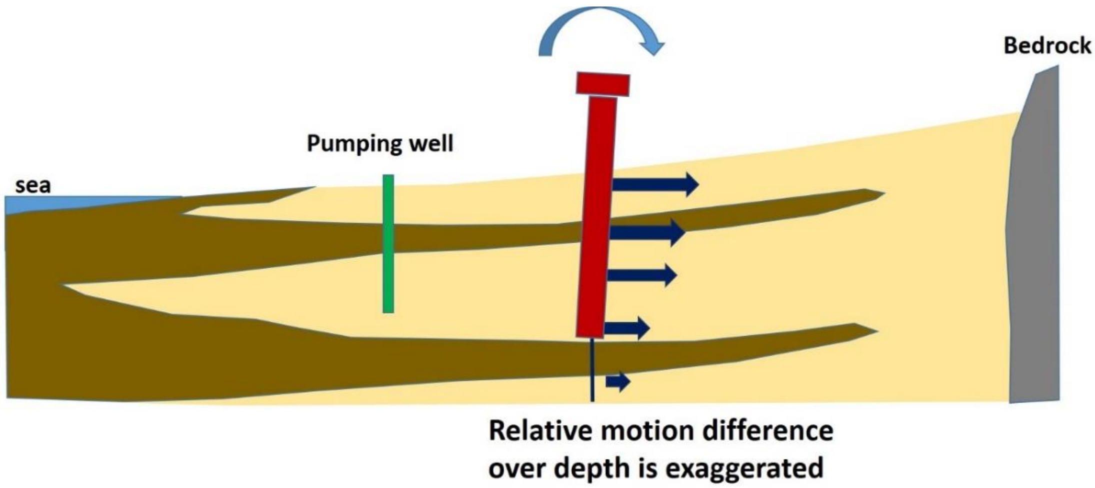

Figure 5 The pillars are deep enough to be influenced by the dampening eastward horizontal motion causing the pillars to tilt eastward away from the pumping center near Tuku.

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