EEG-D-21-00076R2
Appendix A

Land Subsidence due to Creep of the Gulf Coast Aquifer System in the Houston-Galveston Region

YI LIU*, JIANG LI

Appearance of Secondary Consolidation at Borehole Extensometer South West

The historical lowest hydraulic head (HLHH) was set to be -21.35 m before groundwater withdrawal in HAGM model (Kasmarek, 2013) for the aquitards within the two aquifers. From Figure 8 during period I (4 April 1980 ~ 16 August 1990), Groundwater levels in the Chicot and Evangeline aquifers were from -65 to -85 m and from -92 to -121 m, respectively. Both remained much lower than the HLHH -21.35 m that is related to preconsolidation stress, which means that current stress is larger than the preconsolidation one. As a result, the inelastic compaction dominated the subsidence at this location: $\dot{S}(t)$ was 46.92 mm/yr from 1980 to 1987 then decreased to 31.46 mm/yr from 1988 to 1990. The subsidence characteristic during period I would be $\dot{S}_{p-v} \gg \dot{S}_{p-e} + \dot{S}_c > 0$. During periods II (16 August 1990 to 25 March 1993), groundwater levels in the Chicot and Evangeline aquifers were raised from -83 to -60 m and from -118 to -82 m, respectively. The 23 m and 36 m groundwater level rise caused a land rebounding rate of 14.9 mm/yr ($\dot{S}(t) = -14.9$ mm/yr). Therefore, the elastic rebounding of the two aquifers dominated the deformation at this location. The subsidence characteristic in period II will be that $\dot{S}_{p-e} < 0, \dot{S}_{p-v} + \dot{S}_c > 0$, respectively, but the cumulative land subsidence $\dot{S} = \dot{S}_{p-v} + \dot{S}_{p-e} + \dot{S}_c < 0$. During period III (25 March 1993 to 22 January 1998), groundwater levels in the Chicot and Evangeline aquifers were further raised about 12 m to reach -51 m and about 9 m to -72 m, respectively. Meanwhile, the 9 to 12 m trend in groundwater level recovery did not cause further land rebounding although

the elastic compaction rate $\dot{S}_{p-e}$ is less than zero. The trend in the subsidence rate approaches approximately zero, which implies $\dot{S}_{p-v} + \dot{S}_c > 0$ and $\dot{S}_{p-v} + \dot{S}_c \approx -\dot{S}_{p-e}$ from equation (3). Thus, the elastic rebounding of the two aquifers approximately offset the combination of inelastic compaction and secondary consolidation at this location, of which the inelastic deformation is dominate due to the delayed compaction under previous loading. The subsidence characteristic during period III would be that $\dot{S}_{p-e} < 0, \dot{S}_{p-v} + \dot{S}_c > 0$ and the total $\dot{S} = \dot{S}_{p-v} + \dot{S}_{p-e} + \dot{S}_c \approx 0$. During period IV (22 January 1998 to 20 September 2000), groundwater levels in the Chicot and Evangeline aquifers were lowered about 17 m to -65 m and about 13 m to -82 m, respectively. The 13 to 17 m groundwater level lowering caused land subsidence in trend and the elastic compaction rate $\dot{S}_{bp-e}$ is dominant and larger than zero. The inelastic deformation from aquitards within the two aquifers had continued more than about 21 yrs with a decreasing rate $\dot{S}_{p-v}$, which approached zero ($\dot{S}_{p-v} \to 0$) within this period, since the regional lowest groundwater levels happened due to the maximum groundwater withdrawal during 1977 to 1984. The subsidence characteristic during period IV would be $\dot{S}_{p-e} > 0, \dot{S}_{p-v} \to 0$ and $\dot{S} = \dot{S}_{p-v} + \dot{S}_{p-e} + \dot{S}_c > 0$. During period V (20 September 2000 to 18 September 2003), groundwater levels in the Chicot and Evangeline aquifers were raised again about 5 m to -50 m and about 10 m to -70 m, respectively. The 5 to 10 m groundwater level rise neither caused further land rebounding nor significant subsidence in trend. This happened only when inelastic compaction ceased ($\dot{S}_{p-v} \approx 0$) and when elastic rebounding offset secondary consolidation ($\dot{S}_c \approx -\dot{S}_{p-e}$). Thus, it appears that the delay in compaction from inelastic specific skeletal storage of aquitards within the Chicot and Evangeline aquifers at borehole extensometer site Southwest ceased during or before 2000. The subsidence characteristic in period V would be $\dot{S}_{p-e} < 0, \dot{S}_{p-v} \approx 0$ and $\dot{S} = \dot{S}_{p-e} + \dot{S}_c \approx 0$. During the last

period VI (18 September 2003 to 2 December 2017), groundwater levels in the Chicot and Evangeline aquifer exhibited an almost stable trend of 1.13×10^{-4} m/day (Figure 8) (-0.03 m/yr, Table 3) and 4.59×10^{-4} m/day (Figure 8) (0. 14 m/yr, Table 3), respectively. This leads to a conclusion that the trend in elastic compaction can be considered negligible ($\dot{S}_{p-e} \approx 0$). Only secondary consolidation emerged ($\dot{S}_c > 0$) since both $\dot{S}_{p-e} \approx 0$ and $\dot{S}_{p-e} \approx 0$. Thus the subsidence characteristic in period V would be $\dot{S}_{p-e} \approx 0, \dot{S}_{p-v} \approx 0$ and$\dot{S} = \dot{S}_{p-v} + \dot{S}_{p-e} + \dot{S}_c \approx \dot{S}_c = 0.0104$ mm/day (Figure 8) (3.80 mm/yr) as a pseudo-constant. The above detailed analysis is from (Liu et al., 2019). From equation (6), the observation period Δt for the above creep period VI is 14 years, which is the longest one among the 13 extensometers in Table 2. The secondary consolidation time t in equation (6) for the Quaternary and Tertiary sediments can be estimated to have been more than 1000 years since the youngest and uppermost sediments of the Holocene Chicot aquifer were formed in the Greenlandian Age (4200 to 8200 years ago) and the Northgrippiaan Age (8200 to 11,700 years ago) (Liu et al., 2019). The pseudo-constant secondary consolidation rate $\dot{S}_c(t)$ of 3.80 mm/yr during the observation period (Δt) of 14 years (2003 to 2017) if 1.38% subsidence rate change from equation (6) or Figure 5 can be ignored for 1000-year creep.