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Study on Changes in Groundwater Level Decline Rates on Slopes

CORRESPONDENCE →



AUTHORS & AFFILIATIONS

Ken-Ling Lin ¶*

Wei Fang

Min-Xi Xie

Chen-Kan Liao

Ying-Han Chen

¶ Computer Science, Rajiv Gandhi Bhopal, India

ABSTRACT

This study used a Sanlien VW-dot data logger and vibrating-wire electronic piezometers to record continuous groundwater level data from monitoring wells at one-hour intervals. We attempted to stratify the subsurface by analyzing changes in groundwater level decline rates. The observations indicate that the decline rate (slope) generally decreases with depth, which may reflect lower fracture density and connectivity in rock masses or increased compactness of deeper soil layers. The stratification process selected segments with regular decline rates and grouped segments with similar slopes into the same layer. Better layer boundaries were calibrated using multiple line segments with different slope values and depth ranges. Regular decline slopes usually appear several hours after rainfall and are related to local geology, hydrology, and lithology. Because fracture saturation and seepage-equilibrium times differ, the onset time of regular slopes also differs. During stratification, obvious interference from subsequent rainfall should be avoided. In addition, some boundaries still show identifiable differences in variability, so sublayers can be further defined; the causes of these differences are discussed in the paper. Overall, decline-rate stratification generally decreases with depth and is related to weathering, effective fracture ratio, or RQD from shallow to deep strata. Engineering factors, such as horizontal drainage from catch wells and the compaction quality of backfilled trench areas after underground pipeline works, can also affect layer thickness.

Index Terms: Groundwater Level • Decline Rate • Slope Monitoring • Subsurface Stratification • Piezometer • Hydraulic Conductivity

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CONFLICTS

The authors declare no conflict of interest.

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Ken-Ling Lin*



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RESEARCH ARTICLE

Study on Changes in Groundwater Level Decline Rates on Slopes

Ken-Ling Lin^{✉*}, Wei Fang[✉], Min-Xi Xie[✉], Chen-Kan Liao[✉], and Ying-Han Chen[✉]

AFFILIATIONS

[✉] Computer Science, Rajiv Gandhi Bhopal, India

Abstract

This study used a Sanlien VW-dot data logger and vibrating-wire electronic piezometers to record continuous groundwater level data from monitoring wells at one-hour intervals. We attempted to stratify the subsurface by analyzing changes in groundwater level decline rates. The observations indicate that the decline rate (slope) generally decreases with depth, which may reflect lower fracture density and connectivity in rock masses or increased compactness of deeper soil layers. The stratification process selected segments with regular decline rates and grouped segments with similar slopes into the same layer. Better layer boundaries were calibrated using multiple line segments with different slope values and depth ranges. Regular decline slopes usually appear several hours after rainfall and are related to local geology, hydrology, and lithology. Because fracture saturation and seepage-equilibrium times differ, the onset time of regular slopes also differs. During stratification, obvious interference from subsequent rainfall should be avoided. In addition, some boundaries still show identifiable differences in variability, so sublayers can be further defined; the causes of these differences are discussed in the paper. Overall, decline-rate stratification generally decreases with depth and is related to weathering, effective fracture ratio, or RQD from shallow to deep strata. Engineering factors, such as horizontal drainage from catch wells and the compaction quality of backfilled trench areas after underground pipeline works, can also affect layer thickness.

Keywords: Groundwater Level, Decline Rate, Slope Monitoring, Subsurface Stratification, Piezometer, Hydraulic Conductivity

Correspondence: Ken-Ling Lin

1 Background

The study site is a slope in Wenshan District, Taipei (WS-066). Before development, the area was a concave valley-like terrain and a dip slope composed of interbedded sandstone and shale of the Taliao Formation. Geological profiles show that, after backfilling the original valley topography, the soil layer reached a maximum thickness of about 15 m.

Since 2012, groundwater monitoring had shown anomalies. Toe drainage holes were first added at the slope toe. Groundwater levels decreased slightly but did not reach the expected effect. Therefore, slope anchor reinforcement and catch-well construction were carried out from May 2014 to January 2015. After catch-well installation, nearby monitoring wells showed clear dewatering effects, but groundwater levels at mid-slope wells WS-002-S01 and WS-002-S05 remained consistently high.

WS-002-S01 and WS-002-S05 were damaged during pressurized pipeline maintenance in April 2016 and could not be immediately reset. On October 5, 2016, the Wanfang Fire Department reported abnormal yellow muddy flow on the slope. Field inspectors traced the flow source and confirmed that it was caused by rupture and water outflow from a pressurized pipeline. On the same day, the EOW3 groundwater record also showed an abnormal change. Comparison of several days of rain gauge data (hourly cumulative rainfall) and groundwater level observations before the rupture highlights that EOW3,

located approximately 55 m downhill from the rupture, experienced significant anomalous rises independent of rainfall. This high-signal event serves as an excellent real-world "stress test" demonstrating the sensitivity of the monitoring system to pipeline leakages. After pipeline replacement and reinstallation of WS-002-S01 and WS-002-S05, the long-term groundwater level clearly dropped to GL-4.0 to GL-12.0 m below ground surface.

WS-001-S01 (later WS-002-S01) and WS-002-S05 are manual inclinometer boreholes also used for water-level observations. In June 2019, WS-002-S05 was equipped with an electronic water-level gauge with one record per hour, and the electronic monitoring ID was changed to EOW2. While recording at one-hour intervals is standard for long-term monitoring, the rapid, transient rises of Stage I (occurring within an hour) may exhibit aliasing when captured at this frequency. However, because the primary focus of this study is the stable decline rates during Stages II and III, this discrete hourly sampling rate remains appropriate for the analysis.

As shown in Fig. 1, the monitoring setup is organized into three columns. The first column shows the rain gauge readings (daily rainfall in mm, recorded hourly). The second column shows the manual observation data for WS-002-S01 and WS-002-S05 (measured monthly). The third column shows the electronic observation data for WS-066-EOW3 (recorded hourly). The slope observation wells are arranged sequentially from highest to lowest elevation: WS-002-S05 → WS-002-S01 → WS-066-EOW3. In the second column, manual observation

data is missing during Phase III due to borehole and pipeline damage; data resumes in Phase IV after the boreholes were re-established near the original locations. A clear difference in groundwater trends is observed between the early phases (Phases I and II, characterized by pressurized pipeline leakage) and the later phase (Phase IV, following pipeline repair and showing no obvious leakage). In the third column, WS-066-EOW3 shows the attenuation of pipeline leakage effects and a long-term downward trend in the groundwater level following the

construction of two nearby sump wells (Boreholes 1 and 2, which are 5 m in diameter, 10 m deep, and equipped with horizontal drainage holes at approximately 7.8 m depth).

For EOW3, located near the catch well, the groundwater decline rate parameter K' changed significantly before and after catch-well installation. In engineering practice, changes in groundwater decline rate can be used as a reference indicator for checking horizontal-drain dewatering performance and for analyzing slope seepage behavior.

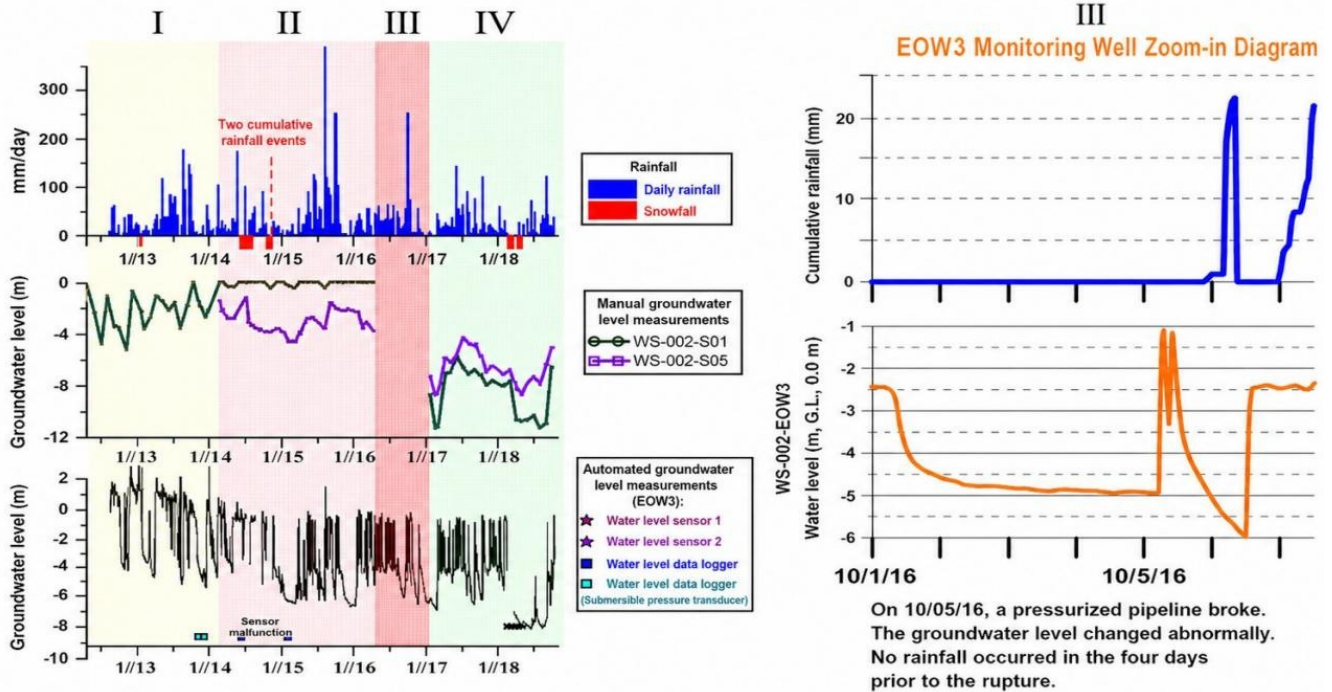


Figure 1. Groundwater observations at the slope from 2012 to 2018 (Stages I-IV), redrawn from Wang et al. [1] and Gao et al. [2].

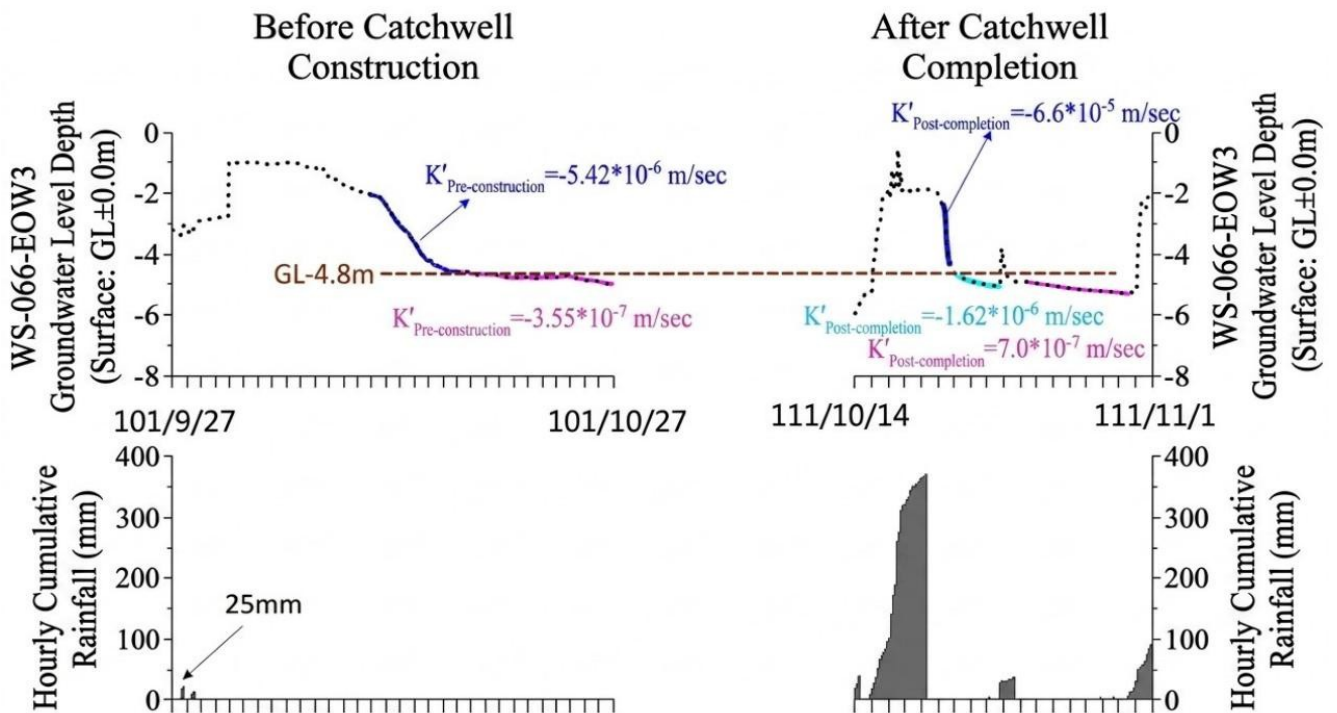


Figure 2. Comparison of EOW3 groundwater decline rates before and after catch-well completion.

2 Method for Stratifying Groundwater Decline Rates

To explain the stratification approach used at WS-066, we first use another slope in Wenshan District, WS-094, as an example by comparing rainfall and groundwater hydrographs. WS-094 is Nankang Formation sandstone with weathered debris at the surface. Stage I is a rising stage in which groundwater rose sharply from about GL-7.0 m to GL-3.0 m within about one hour. Stage II is a decline stage from about GL-3.85 m to GL-5.5 m within about 12 hours, with a decline rate of -4.2×10^{-5} m/s. Stage III shows a slower decline from around GL-5.5 m over about 18 hours, with a decline rate of -4.48×10^{-6} m/s.

During Stage I, rainfall or surface runoff quickly infiltrated underground fractures and caused rapid water rise. This high-transient stage is not suitable for stratification. The stagnation period between Stages I and II is also not suitable. Stages II and III, which show regular decline trends, can be used to distinguish different stratified rates.

The selection of these regular decline segments is evaluated on a case-by-case basis. Because decline thresholds vary across different locations, and there is no universal threshold that applies equally to soil and rock

layers, a qualitative check is supplemented by a consistency review of the decline rate over several hours. To ensure a stable seepage state and exclude transient noise, short-duration downpours occurring after long dry spells must be excluded; under such conditions, water drains rapidly through unsaturated fissures, resulting in temporarily faster and non-representative decline rates. Therefore, the strata must be subjected to rainfall for a sufficiently long period to establish a steady-state or fully saturated seepage regime before decline-rate stratification can be reliably applied.

Using this regular-decline concept, multiple single-line segments with similar rates are classified into the same layer, and the layer boundaries are calibrated for best fit. This is the groundwater decline-rate stratification method. Although current results still cannot directly quantify environmental geological sensitivity, they are related to formation permeability. In future work, additional indicators may be integrated, such as rising-rate versus declining-rate relationships, slope gradient, and other statistical indices.

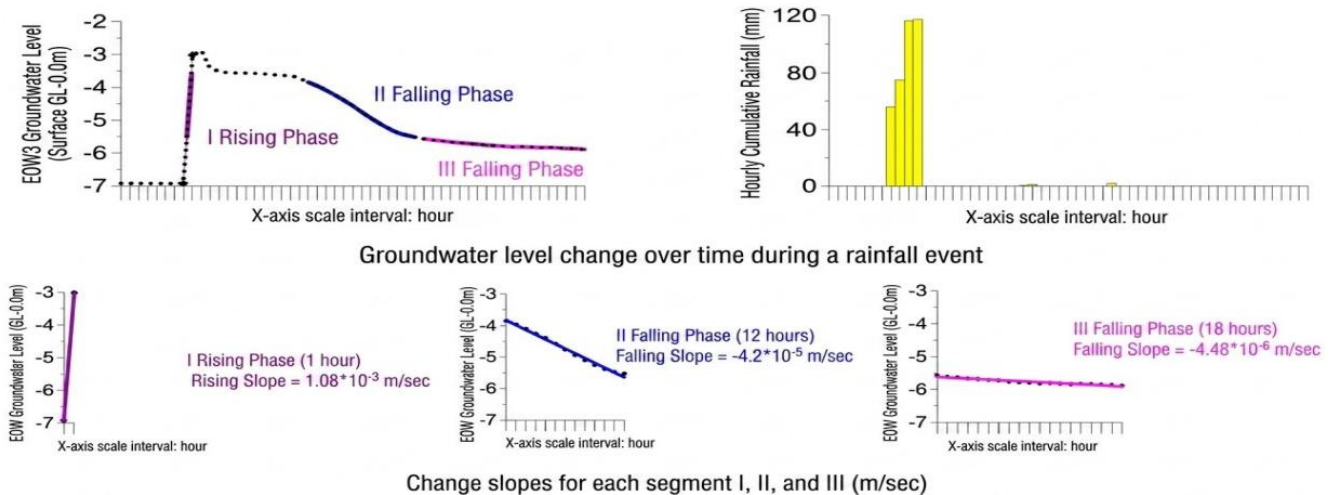


Figure 3. Reference for selecting groundwater decline-rate segments (slope): WS-094 slope.

For WS-066-EOW4, line segments with regular decline rates were selected as stratification references. The selected segments focus on the second layer, decline rates of about $(-1.07$ to $-2.89) \times 10^{-6}$ m/s. The

candidate segments above and below the reference line were compared to refine the boundary between the second and third layers. At present, the boundary between those layers is tentatively set at GL-4.8 m.

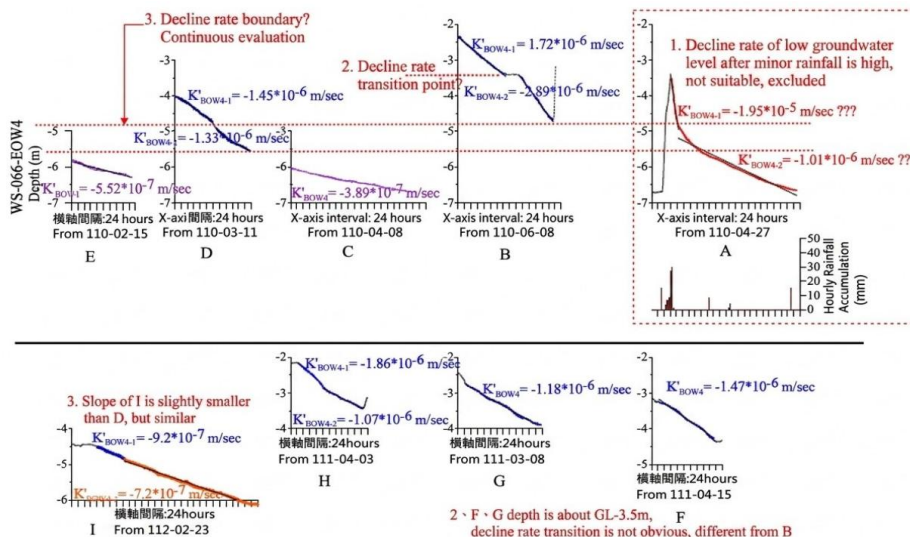


Figure 4. Reference for selecting groundwater decline-rate segments (slope): WS-066 slope.

3 Stratified Profiles and Discussion of Groundwater Decline Rates

3.1 Stratification of Different Groundwater Decline Rates

At this slope, three electronic groundwater monitoring wells are arranged from higher to lower elevation: EOW2 (borehole depth 30 m), EOW4 (15.5 m), and EOW3 (30 m). Their stratifications are summarized below, and the stratified profile is shown in Fig. 5.

EOW2: According to borehole logs, the interval from the surface to about 7.5 m is soil with gravel; 7.5–10 m is weathered sandstone; and 10–30 m is interbedded sandstone and shale. Given the potential for confined-water influence, the geological anisotropy of these interbedded sandstone and shale layers could introduce minor biases in the decline rate calculation compared to the more homogenous overlying soil layers. However, historical monitoring suggests that this influence is relatively small. During the Hualien earthquake on January 3, 2022, where the intensity in Taipei City reached level 4, the hourly groundwater level record (captured approximately 14 minutes post-earthquake) showed a total rise of only 0.73 cm (comprising 0.47 cm and 0.26 cm increases in the two subsequent hourly records), which then gradually decreased over time. Furthermore, comparison of rainfall and groundwater level observations shows a consistent correlation, and the decline-rate stratification boundaries align well with the recorded

depths of soil displacement changes. Nonetheless, the anisotropy of interbedded formations remains a limitation, and monitoring locations with significant confined-water influence should generally be avoided unless calibration methods are available. Although the measured groundwater level may be slightly higher than the actual free-water level, the rise-fall pattern is still consistent with rainfall, and the decline-rate changes remain systematically interpretable; therefore EOW2 is included in the stratified profile.

EOW2 stratification: from ground surface downward, three primary layers are identified. Layer 1 K'_1 extends from GL-0.0 to GL-2.6 m and is subdivided at GL-1.3 m into K'_1a_{EOW2} and K'_1b_{EOW2} . Layer 2 K'_2 is subdivided at GL-4.7 m into K'_2a_{EOW2} and K'_2b_{EOW2} . Layer 3 K'_3 lies deeper than GL-5.8 m.

EOW4: Geological profile interpretation suggests that the 15 m depth is mainly within soil. EOW4 stratification has three primary layers from surface downward: Layer 1 from GL-0.0 to GL-2.1 m, Layer 2 from GL-2.1 to GL-4.8 m, and Layer 3 below GL-4.8 m. The GL-4.8 m boundary between Layers 2 and 3 is tentative and still under evaluation.

EOW3: EOW3 stratification has two primary layers from surface downward. Layer 1 is GL-0.0 to GL-4.8 m and can be subdivided at GL-2.2 m into K'_1a_{EOW3} and K'_1b_{EOW3} . Layer 2 is approximately GL-4.8 to GL-5.1 m.

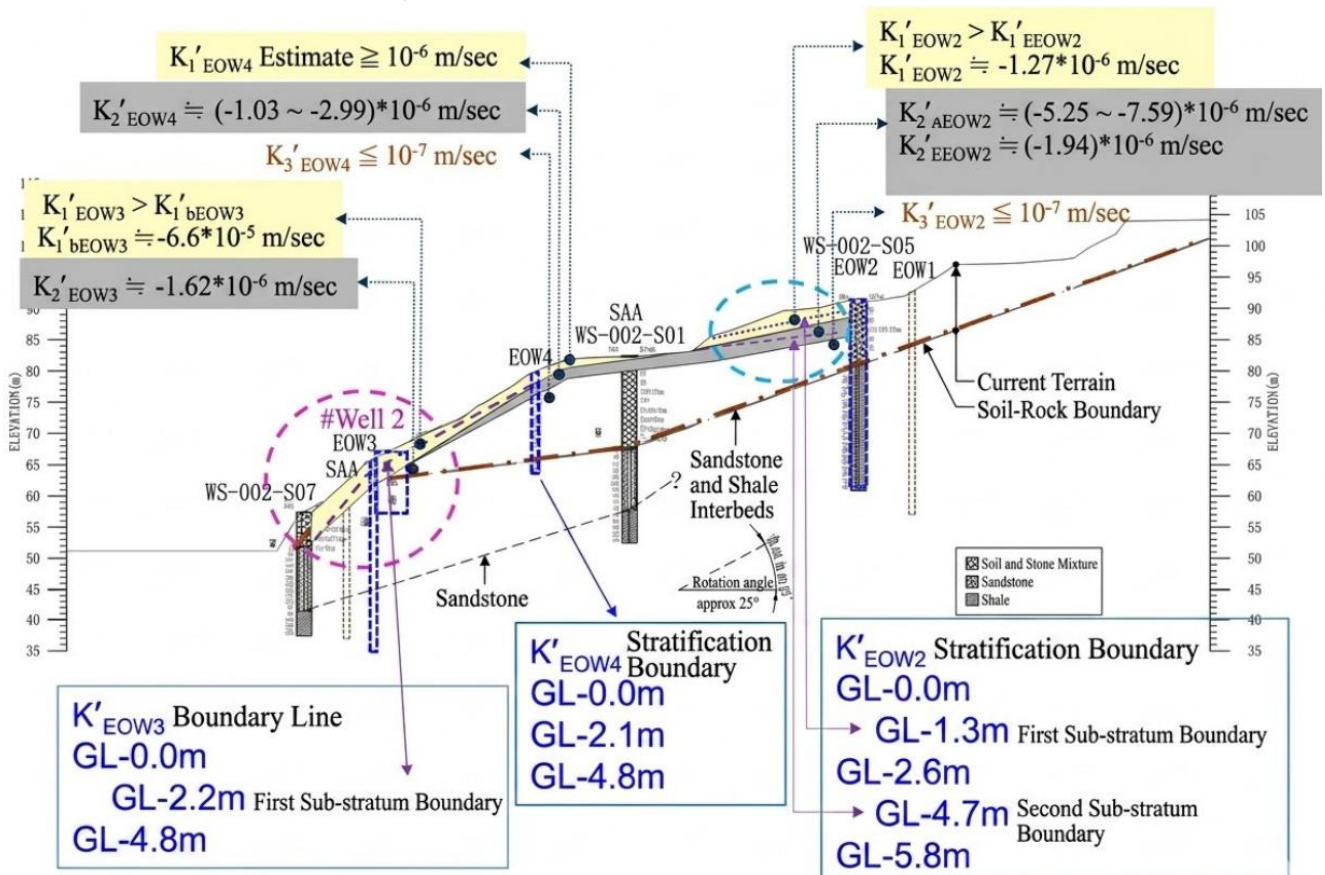


Figure 5. Stratified profile of different groundwater decline rates at WS-066.

3.2 Discussion of Causes of Stratification Differences Among Wells

The total stratified thickness of EOW2 is slightly greater than that of EOW4. A likely reason is that the slope area below EOW2 contains buried pressurized pipelines. Pipeline maintenance or replacement requires excavation and surface restoration, and the restored backfill

zone, visually about 3–4 m deep, may not be fully compacted, resulting in a slightly greater stratified thickness range.

EOW4 has only about two layers within GL-0.0 to GL-4.8 m, unlike EOW2 and EOW3, which can be subdivided further. Since no additional human-induced terrain modification occurred near this observation

Table 1. Stratification of groundwater decline rates at EOW2

Layer	Depth Range (m)	Decline Rate (m/s)
Layer 1 $K'_1 a_{EOW2}$	GL-0.0 to GL-1.3	$K'_1 a_{EOW2} > K'_1 b_{EOW2}$
Layer 1 $K'_1 b_{EOW2}$	GL-1.3 to GL-2.6	-1.27×10^{-5}
Layer 2 $K'_2 a_{EOW2}$	GL-2.6 to GL-4.7	$(-5.25 \text{ to } -7.59) \times 10^{-6}$
Layer 2 $K'_2 b_{EOW2}$	GL-4.7 to GL-5.8	-1.94×10^{-6}
Layer 3 $K'_3 a_{EOW2}$	Below GL-5.8	$\sim 10^{-7}$

Table 2. Stratification of groundwater decline rates at EOW4

Layer	Depth Range (m)	Decline Rate (m/s)
Layer 1 $K'_1 a_{EOW4}$	GL-0.0 to GL-2.1	Estimated $> 10^{-6}$
Layer 2 $K'_2 a_{EOW4}$	GL-2.1 to GL-4.8	$(-1.07 \text{ to } -2.89) \times 10^{-6}$
Layer 3 $K'_3 a_{EOW4}$	Below GL-4.8	Lower than Layer 2 ^a

^aBoundary between Layers 2 and 3 is tentative and under evaluation.

Table 3. Stratification of groundwater decline rates at EOW3

Layer	Depth Range (m)	Decline Rate (m/s)
Layer 1 $K'_1 a_{EOW3}$	GL-0.0 to GL-2.2	$> K'_1 b_{EOW3}$
Layer 1 $K'_1 b_{EOW3}$	GL-2.2 to GL-4.8	-6.6×10^{-5}
Layer 2 $K'_2 a_{EOW3}$	GL-4.8 to GL-5.1	-1.62×10^{-6}

well after development, EOW4 is likely representative of decline-rate stratification in the project backfill area.

Regarding the future application of decline-rate stratification in environmental geological sensitivity analysis, several statistical parameters show promise for quantifying sensitivity based on the current observations. These include: (1) the standard deviation of decline rates within a single stratified layer, which represents layer homogeneity and hydrological anisotropy; (2) the ratio of rising-rate to declining-rate, reflecting fracture connectivity and saturation speed; (3) the coefficient of determination (R^2) from linear regressions of decline segments, indicating the regularity and predictability of the drainage process; and (4) the elevation-dependent variation of decline rates across the slope (e.g., comparing EOW2, EOW4, and EOW3) to characterize spatial heterogeneity. Currently, decline rates must be analyzed on a case-by-case basis for individual slopes, but compiling these statistical indicators across multiple sites could eventually yield standardized sensitivity thresholds.

EOW3 is an existing on-site well with a depth of 30 m and no available drilling log. Nearby drilling records and profiles suggest very shallow weathered soil and sandstone. Since August 2012, hourly electronic records have shown groundwater rise-fall behavior consistent with rainfall, and no abrupt earthquake-induced rises were identified. EOW3 can therefore be treated as a free-water observation well. Before catch-well construction, even small rainfall could rapidly raise groundwater to around GL-1.0 m below the surface, followed by very slow decline. The large difference in decline rates before and after completion of the catch well indicates that EOW3 decline rates are significantly affected by dewatering from the horizontal drains installed with the catch well. Groundwater decline rate can therefore be used as a reference indicator for catch-well performance checks and later maintenance. Proposing specific dewatering maintenance thresholds would significantly enhance the engineering utility of these observations. Based on the long-term observation data of WS-066-EOW3, a groundwater depth of GL-2.0 m and a groundwater decline rate of -6.6×10^{-5} m/s serve as critical baseline indicators. Under typhoon or heavy rain conditions, the groundwater level should drop immediately after the rainfall decreases or stops. A lack of

significant drop indicates drainage hole clogging or active pipeline leakage, which can be confirmed by comparing the response to the rain gauge. Conversely, during dry periods with no rainfall, any small anomalous water-level increase is easily diagnosed as a pressurized pipeline leak. These proposed thresholds and diagnostic actions are summarized in Table 4. Because these indicators depend directly on the well's distance from the catch well and local geological strata, they are case-specific and cannot be generalized without local calibration.

Table 4. Proposed Maintenance and Inspection Thresholds for Catch-Well EOW3

Observation Indicator	Threshold / Range	Implied Condition / Diagnosis	Recommended Action
Post-rainfall decline rate K'	$\geq -6.6 \times 10^{-5}$ m/s (i.e., slower rate)	Possible drain clogging or pipeline leakage	Perform rain comparison; inspect/clean drains
Dry-season groundwater level	Anomalous rise or stabilization above GL-2.0 m	Active pressurized pipeline leakage	Conduct pressure testing and leak tracing
Normal decline rate K'	Consistent with Table 3 values	Normal drainage and seepage behavior	Routine periodic maintenance

Note: These thresholds are case-specific to the geology and catch-well configuration of WS-066-EOW3 and cannot be generalized without local calibration.

4 Conclusions

1. Stratified decline rates generally decrease with depth. This trend is likely related to hydrology and geological weathering. Layer thickness may also be influenced by slope gradient, geomaterial properties, bedding attitude, hydrology, and local engineering conditions.
2. At EOW2, the total thickness of Layers 1 and 2 is slightly greater than at EOW4. A likely reason is that the buried pressurized pipeline area below EOW2 underwent excavation and surface restoration during maintenance or replacement. The restored backfill zone, visually about 3–4 m deep, may have been disturbed or incompletely compacted, causing slightly greater layer thickness and faster decline rates. At EOW4, where no subsequent terrain modification occurred after development, groundwater decline rates below GL-2.1 m are relatively low.
3. At EOW3, decline rates can be used to evaluate horizontal-drain dewatering effectiveness before and after catch-well construction. They can also support long-term performance checks after years of operation and serve as an important reference for catch-well maintenance management.

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