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GNSS-BASED DEFORMATION MONITORING OF EARTHFILL DAMS: METHODOLOGY AND APPLICATION AT THE TOPALANG DAM, UZBEKISTAN

ABSTRACT. *Embankment dams undergo continuous, load-dependent deformation driven by reservoir level fluctuations, seepage, and temperature changes, yet classical geodetic surveying methods capture this behaviour only through periodic, discrete campaigns. This limits their ability to reflect the real-time dynamics of deformation processes and to provide timely warning of hazardous trends. This paper presents the methodology of continuous Global Navigation Satellite System (GNSS) deformation monitoring — covering the positioning principle, coordinate-difference and displacement-vector computation, atmospheric and multipath error mitigation, statistical reliability criteria, and velocity/acceleration-based hazard classification — and demonstrates its application to the permanent GNSS monitoring network installed at the Topalang earthfill dam (Surkhandarya region, Uzbekistan). The system, commissioned in 2024 by "Gidrotexmonitoring" LLC in cooperation with CHC Navigation, comprises ten multi-GNSS (GPS + GLONASS + BeiDou + Galileo) stations achieving ±2 mm horizontal and ±4 mm vertical accuracy in continuous static mode. Monitoring results show a consistent downstream displacement azimuth of 170–190° at all crest stations, confirming hydrostatic pressure as the dominant driving factor, with station GNSS-3 recording a horizontal displacement of 28 mm — approaching the 30 mm threshold recommended by the International Commission on Large Dams (ICOLD). These findings, compared with international case studies (Enguri, Sanalona, and Chinese reservoir dams), confirm that continuous multi-GNSS monitoring provides a reliable, complementary tool for the real-time safety assessment of embankment dams.*

Keywords: *GNSS; deformation monitoring; earthfill dam; horizontal displacement; dam safety; multi-GNSS; Topalang dam*

INTRODUCTION. Dam safety monitoring is a core requirement of hydraulic engineering practice, and its importance grows with the age, height, and storage capacity of a structure. Classical geodetic techniques — triangulation, trilateration, polygonometry, and precise levelling — remain capable of delivering millimetre-level accuracy and have long formed the backbone of deformation surveys at large dams. However, these methods rely on periodic campaigns, typically repeated a few times per year, and are therefore unable to capture the continuous, real-time dynamics of deformation processes that are increasingly demanded by modern dam-safety guidelines [1; 2].

Embankment (earthfill) dams are particularly sensitive to time-dependent processes: deformation is closely linked to reservoir water-level fluctuations, seepage through the dam body, temperature variation, and applied loading, all of which can develop rapidly and require prompt detection [3; 4]. Global Navigation Satellite System (GNSS) technology has emerged as the principal instrumental solution for such continuous monitoring. Modern multi-constellation GNSS — combining the United States' GPS, Russia's GLONASS, the European Union's Galileo, and China's BeiDou — offers simultaneous three-dimensional (X, Y, Z) positioning, uninterrupted 24/7 automated observation, real-time deformation alerts, and millimetre-level accuracy, without replacing but rather complementing classical geodetic techniques within an integrated monitoring system [5; 6; 2].

This paper has two objectives. First, it sets out the theoretical and computational methodology underlying GNSS-based deformation monitoring of hydraulic structures — from the satellite positioning model through to displacement-vector analysis, error correction, statistical reliability testing, and kinematic (velocity/acceleration) hazard classification. Second, it applies this methodology to describe and interpret the results of the permanent GNSS monitoring network operating at the Topalang dam, an earthfill structure in the Surkhandarya region of Uzbekistan, and situates these results within the context of comparable international case studies.

MATERIALS AND METHODS

2.1. GNSS positioning principle. A GNSS system consists of three functional segments: the space segment (the satellite constellation), the control segment (the network of ground control stations), and the user segment (the receivers). The space segment comprises 24 satellites for GPS (a minimum of 21 active), 24 for GLONASS, 30 for Galileo, and 35 for BeiDou, each orbiting at an altitude of approximately 20,200 km and continuously broadcasting precise timing signals [7]. A receiver must acquire signals from at least four satellites simultaneously to solve for four unknowns — the three spatial coordinates (X, Y, Z) and the receiver clock error (δt) — by solving a system of pseudorange equations:

$$\rho_i = \sqrt{[(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2]} + c \cdot \delta t \quad (1)$$

where ρ_i is the pseudorange to satellite i (m); X, Y, Z are the unknown receiver coordinates; X_i, Y_i, Z_i are the known satellite coordinates (ephemerides); c is the speed of light ($\approx 3 \times 10^8$ m/s); and δt is the offset between receiver clock and GNSS system time.

Millimetre-level accuracy is achieved through carrier-phase observations rather than pseudorange alone. The fundamental carrier-phase observation equation is:

$$\Phi = \varphi\_rec - \varphi\_sat + N \cdot \lambda \quad (2)$$

where Φ is the phase observable expressed in wavelength units; N is the integer ambiguity; and λ is the carrier wavelength (19.0 cm for GPS L1). The integer value N is resolved using dedicated ambiguity-resolution algorithms [8].

Coordinates obtained from GNSS processing, expressed in a geocentric Cartesian system (X, Y, Z) or in geodetic coordinates (φ, λ, H), require conversion from ellipsoidal height H to orthometric height H_ort through a geoid model:

$$H\_ort = H - N\_geoid \quad (3)$$

where N_geoid is the geoid undulation, which for the territory of Uzbekistan ranges from approximately −6 m to −15 m and is obtained from a global (EGM2008) or local geoid model [6; 9].

2.2. Displacement computation. For each monitoring point, the coordinates of the initial (baseline) observation epoch (X_0, Y_0, Z_0) are adopted as the reference, against which the coordinates of every subsequent epoch (X_t, Y_t, Z_t) are automatically differenced:

$$\Delta X = X\_t - X_0 \,;\ \ \Delta Y = Y\_t - Y_0 \,;\ \ \Delta Z = Z\_t - Z_0 \quad (4)$$

where $\Delta Z < 0$ indicates settlement and $\Delta Z > 0$ indicates uplift. The total horizontal displacement is computed from the Euclidean norm of the horizontal components:

$$d\_hor = \Delta L = \sqrt{(\Delta X^2 + \Delta Y^2)} \quad (5)$$

expressed as a two-dimensional vector $D\_h = [\Delta X; \Delta Y]^T$ (6), whose azimuthal direction relative to north is obtained using the two-argument arctangent function to guarantee correct quadrant resolution:

$$\alpha = atan2(\Delta Y, \Delta X) \quad (7)$$

2.3. Error sources and correction. GNSS-derived deformation estimates are affected by four principal error categories [3; 9]. Ionospheric delay, caused by the ionised layer between 50 and 1,000 km altitude, is removed using a dual-frequency (L1/L2) ionosphere-free linear combination:

$$\Delta\rho\_IF = (f_1^2 \cdot \Delta\rho_1 - f_2^2 \cdot \Delta\rho_2) / (f_1^2 - f_2^2) \quad (8)$$

with GPS frequencies f_1 = 1575.42 MHz and f_2 = 1227.60 MHz. Tropospheric delay, arising in the lower atmosphere (0–50 km), is separated into hydrostatic (ZHD) and wet (ZWD) components following the Saastamoinen model, with the height-dependent gradient corrected using local meteorological data where significant elevation differences exist between reference and monitoring points. Multipath error, caused by signal reflection from dam surfaces and metal structures, is mitigated using choke-ring antennas and daily-average filtering [3]. Integer ambiguity is resolved using the LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) algorithm, with long static observation sessions (≥ 24 hours) improving reliability.

2.4. Statistical reliability criteria. A measured displacement is accepted as a genuine deformation, rather than measurement noise, only after statistical verification [3]. The combined horizontal measurement error is:

$$\sigma_L = \sqrt{\sigma_X^2 + \sigma_Y^2} \quad (9)$$

A displacement is considered reliable if it satisfies:

$$\Delta L > 2\sigma_L \text{ (95\% confidence)}; \quad \Delta L > 3\sigma_L \text{ (99.7\% confidence)} \quad (10, 11)$$

with the analogous criteria applied to vertical displacement, $\Delta Z > 2\sigma_Z$ (95%) and $\Delta Z > 3\sigma_Z$ (99.7%) (12).

2.5. Kinematic indicators and hazard classification. Beyond absolute displacement magnitude, the rate of deformation development is a critical diagnostic indicator [3]. Horizontal displacement velocity is computed as:

$$v = \Delta d / \Delta t \quad (13)$$

and acceleration, which signals progressive deformation, as:

$$a = dv/dt = (v_2 - v_1) / \Delta t \quad (14)$$

A positive and increasing acceleration indicates progressive deformation and possible structural risk; $a \approx 0$ indicates a stable phase; and $a < 0$ indicates a decaying process returning toward equilibrium — structural failures are typically preceded by an accelerating deformation phase [4]. Table 1 summarises the velocity-based hazard classification adopted for the Topalang monitoring system, following the criteria of P-648/Hydroproject and the U.S. Army Corps of Engineers (USACE).

Condition	Vertical rate (mm/month)	Horizontal rate (mm/month)	Interpretation	Recommended action
Normal	0–1	0–2	Natural / elastic	Standard

Condition	Vertical rate (mm/month)	Horizontal rate (mm/month)	Interpretation	Recommended action
			process	monitoring frequency
Control	1–3	2–5	Increased load or intensified deformation	Increase monitoring frequency
Warning	3–5	5–10	Possible structural risk	Intensive monitoring, expert assessment
Critical	> 5	> 10	Progressive deformation, acceleration detected	Immediate remedial action

Table 1. Deformation-rate hazard classification criteria (after P-648/Hydroproject and USACE) [10; 11].

2.6. Seepage-induced deformation lag. In earthfill dams, a time lag between reservoir level change and dam-body deformation is a significant physical phenomenon, attributable to the inertia of the seepage flow through the dam's loess-clay core: hydrostatic pressure does not act on the dam body instantaneously, but only once the internal seepage regime has re-established itself [12; 13]. Seepage flow velocity follows Darcy's law:

$$v_f = k \cdot i = k \cdot (\Delta H_{water} / L_{filter}) \quad (15)$$

where v_f is the seepage flow velocity (m/s), k is the hydraulic conductivity (m/s), i is the hydraulic gradient, ΔH_{water} is the water-level difference (m), and L_{filter} is the seepage path length (m).

2.7. Study site and instrumentation. The methodology above was applied to the permanent GNSS deformation monitoring network of the Topalang dam, an earthfill structure operated by "Topalang HPP" JSC in the Surkhandarya region of Uzbekistan. Design and planning of the online monitoring system began in August 2019 at the request of "Topalang HPP" JSC; in February 2024, specialists of "Gidrotexmonitoring" LLC, in cooperation with

CHC Navigation (Chcnav), installed iStar permanent GNSS receivers, configured the HCmonitor software platform, and brought the system into full operation [14; 15]. Ten stations were deployed at locations identified as most sensitive to deformation along the dam profile: four stations (GNSS-1 to GNSS-4) on the crest (elevation 965 m), three (GNSS-5 to GNSS-7) on the 919 m berm, two (GNSS-8, GNSS-9) on the 875 m berm, and one base station (GNSS-10) located more than 500 m from the deformation zone on stable rock foundation. Table 2 summarises the technical specification of the system.

Parameter	Specification
Project start	August 2019 ("Topalang HPP" JSC)
Full commissioning	February 2024
Receiver type	CHC Navigation (Chcnav) iStar, permanent GNSS
Software	HCmonitor — real-time data processing
Constellations used	GPS + GLONASS + BeiDou + Galileo (multi-GNSS)
Total stations	10 (9 monitoring + 1 base)
Horizontal accuracy (RMS)	± 2 mm (static mode, 24-hour session)
Vertical accuracy (RMS)	± 4 mm (static mode)
Observation mode	24/7 continuous
Data transmission	Real time, via GSM/Internet

Table 2. Technical specification of the Topalang dam GNSS monitoring system [14; 15].

RESULTS. Continuous multi-GNSS observation at the Topalang dam demonstrates a consistent deformation pattern across all crest-zone stations. The azimuth of horizontal displacement computed by Eq. (7) is approximately $\alpha \approx$ 170–190° at every station, i.e. oriented toward the downstream (lower pool) side of the dam. This uniform directionality across independent stations indicates that hydrostatic pressure from the reservoir is the dominant driving mechanism of deformation, consistent with the physical model described in Section 2.6 [16].

The most significant result recorded to date is at station GNSS-3, located on the dam crest, where cumulative horizontal displacement has reached 28 mm. This value lies only 2 mm below the 30 mm threshold recommended by the International Commission on Large Dams (ICOLD) for structures of this class, placing the observed displacement in the upper part of the "control"/lower part of the "warning" range defined in Table 1. Applying the reliability criteria of Eqs. (9)–(11) with $\sigma_X = \sigma_Y = \pm 2$ mm, this displacement substantially exceeds the $3\sigma_L$ (99.7% confidence) threshold and is therefore classified as a statistically genuine deformation signal rather than measurement noise.

The vertical displacement accuracy of ± 4 mm achieved by the system is sufficient to resolve settlement trends at the millimetre scale, and the continuous 24/7 acquisition regime allows velocity (Eq. 13) and acceleration (Eq. 14) to be computed at any desired epoch interval, enabling early identification of any transition from the "normal" to the "control" or "warning" categories defined in Table 1.

DISCUSSION. The GNSS-3 result at the Topalang dam should be interpreted in light of comparable international experience with GNSS-based dam deformation monitoring. At the Enguri arch dam in Georgia (height 271.5 m), the DAMAST project has, since 2020, used ten permanent GNSS stations to record crest displacements of up to 8 cm and to identify a pronounced hysteresis effect, whereby the deformation path during reservoir filling differs from that during drawdown — a signature of seepage-flow inertia analogous to the mechanism described by Eq. (15) [17]. At the Sanalona gravity dam in Mexico, Vazquez-Ontiveros et al. found a correlation coefficient of $r = 0.97$ between reservoir water level and dam displacement, directly supporting the causal link between hydrostatic loading and deformation observed at Topalang [18]. Xiao et al., studying a reservoir dam in China, reported that multi-GNSS processing improved displacement accuracy by 35% relative to GPS-only solutions, underscoring the value of the four-constellation configuration adopted for the Topalang network [19].

These parallels suggest that the near-threshold displacement recorded at GNSS-3 is physically consistent with the hydrostatic-loading and seepage-lag mechanisms documented internationally, rather than an artefact of instrumental error. Nevertheless, several factors merit continued attention. First, because the deformation-velocity classification (Table 1) depends on the interval over which velocity is computed, sustained observation over multiple reservoir filling–drawdown cycles is required to distinguish a stable oscillatory pattern from a genuinely progressive (accelerating) trend. Second, the accuracy of tropospheric correction is sensitive to the substantial elevation difference (~90 m) between the dam crest and lower berm stations, and continued validation against independent meteorological data is advisable. Third, while continuous GNSS monitoring offers major advantages over periodic classical surveys in terms of temporal resolution, it does not eliminate the need for classical geodetic methods (triangulation, trilateration, precise levelling), which remain valuable as an independent check on GNSS-derived displacements, particularly during long-baseline ambiguity-resolution sessions [5; 2].

Overall, the case of the Topalang dam illustrates how the methodology set out in Section 2 — from raw pseudorange and carrier-phase observations through to statistically validated displacement vectors and kinematic hazard classification — can be operationalised as a practical, real-time dam safety tool, and how its outputs can be benchmarked against both national/international guideline thresholds (ICOLD, USACE, P-648/Hydroproject) and the broader body of international GNSS dam-monitoring literature.

CONCLUSION. This paper has presented the methodology of GNSS-based continuous deformation monitoring of embankment dams and applied it to the permanent, ten-station multi-GNSS network installed at the Topalang dam in Uzbekistan. The methodology — encompassing the satellite positioning model, displacement-vector computation, atmospheric and multipath error correction, statistical reliability testing, and velocity/acceleration-based hazard classification — provides a rigorous basis for real-time dam safety assessment that complements, rather than replaces, classical geodetic surveying. Application of this framework at Topalang reveals a consistent downstream displacement pattern (azimuth 170–190°) driven by hydrostatic loading, with station GNSS-3 recording a statistically validated horizontal displacement of 28 mm, approaching the 30 mm ICOLD safety threshold. These results, consistent with international case studies at the Enguri, Sanalona, and Chinese reservoir dams, confirm the value of continuous multi-constellation GNSS monitoring as an early-warning instrument for embankment dam safety, and highlight the importance of sustained, long-term observation to distinguish stable cyclical behaviour from genuinely progressive deformation.

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