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Settlement Monitoring of Large Storage Tanks Using a Hydrostatic Leveling System

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Abstract: Accurate long-term settlement monitoring of large storage tanks is frequently degraded by environmental disturbances, including temperature, gravity variations, pipeline pressure fluctuations, and sensor noise. To address these limitations, a multi-source error cooperative compensation framework based on a hydrostatic leveling system was developed. An Arrhenius-type temperature–density model was first established to enable real-time correction of the working fluid density, while a gravity correction model incorporating latitude and elevation was introduced using the WGS-84 reference system to compensate for spatial variations in gravitational acceleration. Then a differential relative-settlement algorithm was designed to eliminate pressure transmission errors along the connecting pipeline. Subsequently, the compensated settlement signals were fused using a Kalman filter, allowing random noise and abrupt outliers to be simultaneously attenuated. Using the proposed hybrid processing strategy, the root-mean-square error (RMSE) of the settlement time series was reduced by approximately 42% compared with conventional hydrostatic leveling approaches, while overall monitoring accuracy was improved by more than threefold. The results confirmed that the proposed fusion methodology can effectively isolate environmental interference and significantly improve the precision and stability of long-term settlement measurements. This study provides a reliable and high-quality data acquisition framework for the structural health monitoring and safe operation of large storage tanks, particularly under demanding field conditions requiring sustained, high-resolution deformation surveillance.

Keywords: Hydrostatic leveling system; Settlement monitoring; Temperature–gravity compensation; Differential settlement algorithm; Kalman filter; Large storage tanks

1 Introduction

Large oil tanks are critical equipment for national strategic petroleum reserves and commercial oil storage, which are primarily composed of the tank body, foundation, auxiliary facilities, and safety attachments [1]. For large oil tanks that have been in long-term operation or are located in land reclamation areas or regions frequently affected by typhoons, foundation settlement is a key factor influencing their safe operation. Therefore, it is essential to regularly monitor the settlement of tank foundations [2, 3]. Settlement can be categorized into three types based on morphology: Overall settlement, tilting settlement, and differential settlement. Overall settlement typically does not cause tank inclination, stress concentration, or collapse, and is commonly observed in newly commissioned tanks [4]. As a result, settlement monitoring mainly focuses on detecting tilting and differential settlement.

Static leveling, due to its simplicity, high precision, strong stability, minimal susceptibility to external environmental influences, and wide range of applications, is widely used in settlement monitoring of major infrastructures such as subways, bridges, tunnels, dams, and nuclear power plants. Currently, telescopic static level meters are predominantly used for collecting settlement data via static leveling [5, 6]. However, these instruments suffer from drawbacks such as large size, poor sealing, and high sensitivity to external environmental conditions, making them increasingly inadequate for meeting growing demands for high-precision data acquisition [7]. Hydraulic static level meters, on the other hand, offer advantages such as compact size, good sealing, low environmental sensitivity, and a wide measurement range, making them more suitable for settlement monitoring systems in large oil tanks [8, 9]. Nevertheless, hydraulic static level meters are still vulnerable to external disturbances such as atmospheric pressure, temperature, and electromagnetic fields, which can lead to increased drift in settlement measurements over time [10–12].

In static leveling measurements, interfering factors significantly affect measurement accuracy. Researchers have been exploring effective interference compensation algorithms to enhance the precision of static measurements [13]. Static interference mainly includes static drift and environmental disturbances, which can cause measurement results to deviate from true values, thereby compromising instrument reliability. In terms of interference compensation methods, recursive filtering algorithms are widely applied in static characteristic compensation to achieve higher measurement accuracy. For instance, some studies have employed recursive filtering algorithms to compensate for static characteristics, effectively reducing the impact of static noise and improving the accuracy of static level measurements [14]. Additionally, improved algorithms combining differential and dynamic accumulation methods have been proposed for stable and precise static force measurements, demonstrating potential in interference compensation. In the identification and compensation of interference types, static drift is recognized as a major factor affecting measurement accuracy [13].

Relevant research has significantly improved measurement stability and accuracy through the identification and compensation of static drift [15]. Moreover, electric field inversion algorithms, which apply correction via the superposition of potential terms, have effectively mitigated static noise interference and enhanced voltage measurement precision [16]. Differential algorithms also play a crucial role in interference compensation. In differential pressure measurements, for example, the design and optimization of differential pressure elements help reduce interference effects and ensure measurement stability and accuracy [17]. Similarly, differential optical absorption spectroscopy used in gas detection has shown that differential techniques can effectively suppress background interference and improve detection sensitivity and accuracy. Regarding the improvement of static level meter accuracy, the combined use of multiple compensation strategies has been emphasized [18]. For example, composite algorithms that integrate differential algorithms and dynamic accumulation methods can achieve higher measurement accuracy under static conditions. Continuous optimization of static characteristic compensation technologies also provides technical support for ensuring the accuracy of static level meters in practical applications [13].

In summary, interference compensation techniques play a critical role in static leveling measurements. Through the application of various methods such as differential algorithms, recursive filtering, and static drift compensation, the impact of static interference has been effectively reduced, significantly enhancing measurement accuracy. These research findings provide a theoretical foundation and technical pathway for optimizing the performance of static level meters and promoting their application in practical measurement scenarios [14, 15, 18, 19].

This study addresses the issue of insufficient accuracy in settlement monitoring of large oil tanks due to external environmental influences. By employing static level meters in model experiments and applying the Kalman filtering algorithm, the research thoroughly investigates the interference mechanisms of factors such as temperature and gravitational acceleration on settlement data acquisition. A settlement prediction method under environmental compensation conditions is established by integrating a differential settlement algorithm. A settlement monitoring method that fuses multi-source error compensation and filtering processing is proposed, and its effectiveness and robustness are validated through both model experiments and field tests.

2 Measurement Principle and Error Source Analysis

2.1 Working Principle of Hydraulic Static Level Instruments

The basic working principle of static level instruments is based on the "communicating vessels" principle. When the same liquid is introduced into a U-shaped tube that is open at both ends and interconnected at the bottom, the liquid surfaces at both ends can remain level under the same atmospheric pressure and gravitational force when the liquid is static and not flowing.

By treating two interconnected static level instruments as a "U-shaped tube" the relative positional change between measurement points can be inferred by measuring the change in liquid level within the instrument at the target point. Figure 1 illustrates the working principle of the hydraulic static level instrument.

Hydraulic static level systems operate on the principle of communicating vessels, quantifying relative settlement via the measured pressure differential of the liquid column (Figure 1).

$$\Delta \mathrm{H} = \frac{\Delta \mathrm{P_b} - \Delta \mathrm{P_a}}{\rho \mathrm{gs}}$$

2.2 Settlement Interference Analysis

The dominant source of error in hydrostatic leveling is external disturbance—temperature, gravity, acceleration, pressure, vibration, electromagnetic interference, etc.—which alters liquid density, changes the liquid level or corrupts data acquisition. Liquid-density drift can be corrected in real time through temperature compensation.

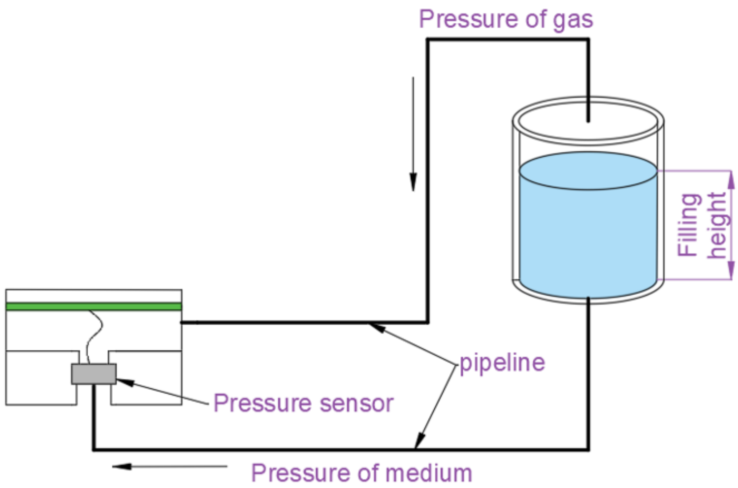

Figure 1. Working principle diagram of the hydraulic static level system

2.2.1 Temperature-induced error

Hydrostatic levelers derive elevation change from the differential pressure of liquid in a connected vessel system. Temperature variations, however, modify the liquid's physical properties (notably density) and thus the measured pressure difference, introducing error. Large tanks are so voluminous that individual sensors may be tens of meters apart; differences in solar exposure or shading create temperature gradients among them. A higher local temperature expands the liquid, raising the sensed level; cooling contracts it, lowering the level. These apparent movements are not true elevation changes and must be removed.

A temperature-compensation algorithm was therefore implemented: A mathematical model that relates temperature to the induced error was used to correct raw readings.

2.2.2 Gravity-related settlement effects

The value of gravitational acceleration (g) varies significantly with latitude and altitude. For large oil tanks, whose safety assessment relies on accurate settlement calculation, the exact local g must be known. Because air density, Earth rotation and elevation all influence g, a different value must be adopted for each altitude band if the tank farm spans a range of elevations.

2.2.3 Complex/differential settlement

Differential settlement of large storage tanks is a multi-factor phenomenon that cannot be ignored. Geology is a primary driver: soft soils, varying stratigraphy or fluctuating groundwater tables all redistribute support stiffness. Foundation design and construction quality are equally critical—insufficient bearing capacity or poor compaction can trigger non-uniform movement. The tank's own weight and the spatial distribution of stored product further distort the load footprint; eccentric filling amplifies subsoil stress imbalance. Operational vibrations and cyclic thermal expansion/contraction continue to rework the substrate long after commissioning. Consequences range from shell distortion, nozzle misalignment and floating-roof seizure to catastrophic rupture and loss of containment. Differential settlement also stresses connecting pipework, raising maintenance cost and outage risk.

Hence, settlement must be controlled at every stage. Geotechnical surveys, foundation redesign, staged loading and strict construction quality control are prerequisites. In service, automated leveling networks should sample continuously; any trend toward non-uniform movement triggers grouting, underpinning or other remediation before allowable limits are exceeded.

3 Error Compensation & Filtering Algorithm Design

3.1 Temperature-Compensation Model

Hydrostatic levelers operate under widely varying environmental conditions. Therefore, the temperature-compensation algorithm must be environmentally adaptive—robust across different temperature spans and rates of change. Designing such an algorithm is a multi-step process that includes experimental measurement, data analysis, model construction and software implementation. A well-formulated compensation scheme can markedly improve measurement accuracy and long-term stability when the ambient temperature drifts. Temperature variations introduce systematic error by altering liquid density. Traditional linear models neglect higher-order terms. An

Arrhenius-type function was adopted in this work as follows:

$$\rho(T) = \rho_0 \exp\left[-\alpha (T - T_0)^2\right]$$

where, $\rho_0 = 1000 \text{ kg m}^{-3}$ (nominal density at 20°C), $\alpha = 8.5 \times 10^{-5}{}^{\circ}\text{C}^{-2}$ (experimentally calibrated), and T_0 = 20°C (reference temperature).

The corrected pressure-to-settlement conversion is as follows:

$$\Delta H = \frac{\Delta P}{\rho(T) g} \frac{\rho(T_0)}{\rho(T)} = \frac{\Delta P}{\rho(T) g} k_{\text{temp}}$$

The temperature-compensation coefficient k varies by approximately ±0.6% over the 0–50°C range and therefore cannot be neglected.

3.2 Gravity-Acceleration Correction

The gravitational acceleration varies with latitude φ and altitude h. The WGS-84 simplified formula can be used as follows:

$$g(\varphi, h) = g_0 \left[1 + 0.005 \sin^2 \varphi - 3.1 \times 10^{-7} h\right]$$

The local gravity acceleration g is obtained from a lookup table. Once the settlement-monitoring system is installed, its latitude and altitude are fixed; consequently, g needs to be determined only once, at start-up, by reading the value corresponding to the installed position from the table and inserting it into the calculation. This procedure guarantees that the computed settlement is both accurate and efficient, providing a solid basis for the safe operation of large oil storage tanks. The reference value is g_0 = 9.780 m s^{-3} (equatorial sea level). Typical corrections for the tank farm are listed in Table 1.

Table 1. Relationship between altitude and water density

Elevation (m) and Latitude (°)	Density (g/cm^3)				
	0	**20**	**40**	**60**	**80**
0	9.78	9.786	9.802	9.819	9.831
500	9.779	9.785	9.8	9.818	9.829
1000	9.777	9.783	9.799	9.816	9.828
2000	9.774	9.78	9.796	9.813	9.823
4000	9.768	9.774	9.789	9.807	9.818

3.3 Differential Settlement Algorithm

The task of a hydrostatic leveling network is to measure the relative settlement of multiple points. All vessels are interconnected by a continuous liquid-filled tube. Each container's liquid height is sensed by the built-in transducer of the corresponding hydrostatic cell. One of the most stable cells is designated as the reference (benchmark); every other cell reports settlement relative to this benchmark, whose elevation and liquid level are assumed constant or known. The differential sampling algorithm is based on simple differencing: It computes the difference between successive readings in time or between adjacent cells in space. This operation highlights changes and suppresses static or slowly varying background information. In signal processing terms, continuous analog levels are converted into discrete increments; only the increments are stored, cutting memory requirements.

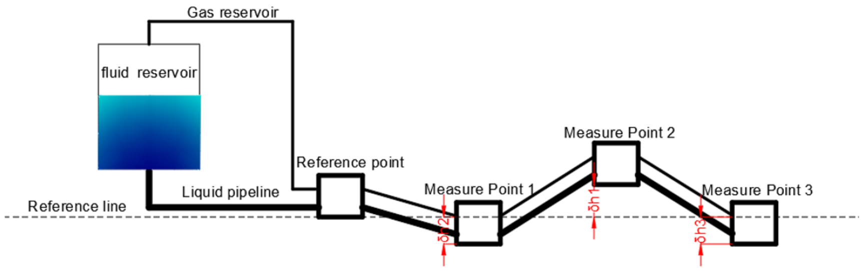

Figure 2. Schematic diagram of the differential algorithm

Conventional settlement algorithms cannot mitigate external disturbances that corrupt raw readings. Differencing, however, provides a first-order rejection of common-mode interference (temperature drift, vibration, electromagnetic pickup, etc.) because such disturbances affect all cells almost equally and are largely canceled when the reference signal is subtracted. The pipework layout is shown in Figure 2.

The pressure variation $\Delta P_{\mathrm{a}}(\mathrm{N})$ caused by environmental interference in a hydrostatic level gauge can be calculated using the following formula:

$$\Delta P_{\mathrm{b}} = P_1 - P_2$$

where, P_1 is the measured pressure value (N) at the reference point of the reference hydrostatic level gauge after installation, and P_2 is the measured pressure value (N) at measurement point 1 of the reference hydrostatic level gauge after settlement or elevation occurs. The pressure variation ΔP_{b}(N) of a hydrostatic level gauge after settlement or elevation can be calculated using the following formula:

$$\Delta P_{\mathrm{b}} = P_1 - P_3$$

where, P_3 is the measured pressure value (N) at measurement point 3 of the reference hydrostatic level gauge after settlement or elevation occurs.

The variation in settlement or elevation ΔH(mm) can be calculated using the following formula:

$$\Delta H = \frac{\Delta P_{\mathrm{b}} - \Delta P_a}{\rho g s}$$

where, ρ is the density of the liquid (10^{-3}g/m^3), g is the local gravitational acceleration, and s is the area of the sensor's sensitive element (mm^3).

It should be noted that the above formulas do not account for the impact of ambient temperature changes on liquid density, external environmental changes on the sensor, or the impact of settlement of the liquid storage tube on hydrostatic level gauge measurements. Although these factors can be excluded to minimize errors, practical situations are complex and actual measurements should be combined with real-world conditions.

3.4 Kalman Filtering Algorithm

In complex environments, data acquisition systems are often affected by various noises and interferences, such as electromagnetic interference, mechanical vibration, temperature changes, etc. To improve data reliability and accuracy, efficient digital filtering algorithms are required. Kalman filtering is an algorithm that utilizes linear system state equations to optimally estimate system states based on system input, output, and observation data. Kalman filtering extracts the desired signal from a mixture of many signals. It is particularly suitable for processing random signals, removing noise through statistical methods, and restoring true data.

The reason for adopting the Kalman filtering algorithm is that its core idea is to use the system's predicted value and actual observation value to obtain the optimal estimate of the system state through a certain algorithmic rule. This process not only considers the dynamic characteristics of the system but also fully considers the impact of observation noise and process noise. Kalman filtering is a recursive estimation, meaning that only the estimated value of the previous state and the observation value of the current state are required to calculate the estimated value of the current state. Therefore, it does not need to record the historical information of observations or estimates. The difference between the Kalman filter and most other filters is that it is a pure time-domain filter. It does not need to be designed in the frequency domain and then converted to the time domain, as low-pass filters and other frequency-domain filters do.

Kalman filtering is mainly divided into prediction and update parts, requiring the construction of the system's state equation and observation equation, as well as the known initial state of the system. In the prediction stage, the filter uses the estimate of the previous state to make an estimate of the current state. In the update stage, the filter uses the observation value of the current state to optimize the prediction value obtained in the prediction stage to obtain a more accurate new estimate. In the prediction step, the current state is predicted based on the state and control quantity of the previous moment. This predicted value is an estimate because it has not yet considered the observation value of the current moment. The error covariance matrix of the predicted value is calculated based on the error covariance matrix of the previous moment and the system noise covariance matrix.

$$\bar{x}_{k|k-1} = F_k \bar{x}_{k-1} + B_k u_k$$

$$P_{k-1|k} = F_k P_{k-1|k-1} F_k^t + Q_k$$

In the update step, the state estimate for the current moment is calculated based on the observation value and the predicted value for that moment. This estimate is a more accurate one because it has already taken into account the observation value of the current moment. The error covariance matrix of the state estimate is calculated using the error covariance matrix obtained in the prediction step, the observation noise covariance matrix, and the Kalman gain.

$$K_k = P_{k|k-1} H_k^T \left(H_k P_{k|k-1} H_k^T + R_k \right)^{-1}$$

$$\bar{x}_{k|k} = \bar{x}_{k|k-1} + K_k \left(z_k - H_k \bar{x}_{k|k-1} \right)$$

$$P_{k|k-1} = \left(I - K_k H_k \right) P_{k|k-1}$$

After deriving the above formulas, the corresponding algorithm for this filtering method can be clearly obtained, and the final results can be calculated by applying the algorithm to the collected data.

Kalman filtering has become one of the most widely used filtering methods, with applications in various fields such as communications, navigation, guidance and control, radar tracking, image processing, and more. For example, in the navigation and control of drones and robots, Kalman filtering is used to estimate state information such as position and speed. In image processing, Kalman filtering is applied for tasks such as image denoising and edge detection.

4 Analysis of Test Results

The accuracy and stability of tank settlement detection instruments in field tests are influenced by various weather changes and environmental factors. Weather factors such as temperature, atmospheric pressure, humidity, and precipitation can lead to deformation of instrument components, reading errors, or measurement interference. Therefore, appropriate protective measures need to be taken during testing. Additionally, fluctuations in wind speed and direction can affect the stability of the measurement instruments, and ground conditions such as loose soil can also introduce errors. To reduce these impacts, a solid ground should be selected as the measurement station, and environmental factors should be fully considered in the experimental design to ensure the accuracy and reliability of the measurement results. During the test analysis, close attention should be paid to weather changes and environmental factors, and corresponding measures should be taken for compensation and correction.

Figure 3 shows the field test platform. The test results indicate that the tank settlement detection instrument exhibits high measurement accuracy and stability in the field, accurately reflecting the ground settlement trend and rate. To ensure measurement accuracy and stability, it is recommended to regularly calibrate and maintain the instrument and fully consider the impact of environmental factors on measurement accuracy. The data collected from the platform is divided into two parts. The upper part shows the relative settlement values of five settlement monitoring instruments, while the lower part displays the real-time temperature data of the instruments. It can be observed that the temperature data is relatively authentic, with some temperature errors among different devices due to varying levels of sunlight exposure, but the temperature trend is normal.

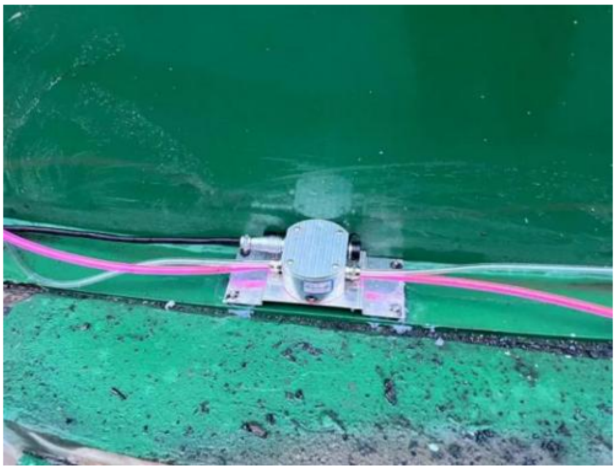

Figure 3. Field test platform

Table 2. Precision test data for settlement

Standard Value (mm)	Common Settlement Algorithm (mm)	Combined Settlement Algorithm (mm)
3	3.3	3.2
5	5.4	5.1
9	9.2	9.1
13	13.4	12.9
Average error	3.25	0.75

After collecting the base point data, the instruments were left to stabilize for a week to ensure data stability. Subsequently, standard blocks of different heights were used to measure each sensor one by one. During data processing, the largest and smallest ten values in each set of data were eliminated to reduce the influence of abnormal values on the results. Then, the average value of the remaining data was calculated. Finally, the settlement acquisition accuracy obtained was compared using a common settlement algorithm and a combined algorithm to assess the differences in accuracy and reliability between the two.

Table 2 shows the precision test data for settlement. As shown in the analysis of test results, the combined algorithm, which integrates the differential settlement algorithm, temperature calibration algorithm, and Kalman filtering, can effectively reduce the impact of the external environment on settlement accuracy and improve settlement acquisition accuracy. The higher the settlement measurement value, the greater the measurement deviation caused by the external environment.

5 Conclusions

This study addressed the practical use of hydrostatic leveling systems for settlement monitoring of large storage tanks. The influence of environmental factors—temperature and gravity acceleration in particular—on measurement accuracy was analyzed systematically. A monitoring strategy that combines (i) a temperature-compensation model, (ii) gravity-acceleration correction, and (iii) Kalman filtering with a settlement differencing algorithm was proposed. Field tests showed that the approach markedly improved both accuracy and stability, suppressed environmental noise, and enhanced overall robustness and adaptability. Nevertheless, the present environmental modeling is still simplified. Circumferential, non-uniform solar heating of the tank shell introduces spatial temperature gradients that a single-point temperature-compensation model cannot resolve; the residual error becomes a new systematic bias. Moreover, settlements are spatially correlated. The current differencing algorithm operates on single-tank time series only, ignoring spatial covariance. When adjacent tanks settle simultaneously, false alarms are generated and thresholds must be relaxed, sacrificing sensitivity.

Future work could introduce a thermo-mechanical coupled finite-element model that takes solar radiation, shell shadowing and convective heat transfer as boundary conditions, and computes in real time the complete chain "temperature gradient → local shell deflection → liquid-level change" thereby enabling spatially distributed compensation. For soft-clay, karst and permafrost regions, transfer-learning-based compensation models could be developed so that the same algorithm can be recalibrated with only a handful of new samples when moving, for example, from a soft-soil site to a permafrost site, facilitating rapid commercial deployment. The results provide reliable data for the safe operation of large storage tanks and offer a technical reference for long-term settlement monitoring of similar engineering structures. Future research could extend the method to complex geological settings and multi-source disturbance environments, pushing settlement monitoring technology toward higher precision and greater intelligence.

Author Contributions

Writing—original draft preparation, T. T. W.; writing—review and editing, Q. F.; visualization, S. W. C.; supervision, J. Z.; project administration, Z. T. L.; funding acquisition, Y. L. Y.; data curation, H. Y. G. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data supporting our research results are under privacy or ethical restrictions. The data are available from [Tingting Wu, wutingting_sc@cnpc.com.cn] for researchers, who meet the criteria for accessing confidential data.

Conflicts of Interest

The authors declare no conflict of interest.

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