Academic Education Publishing House

*Industry Science and Engineering Vol. 3 No. 8, 2026*

# Water-Pressure Boundary Formation and Anti-Flotation Safety of Underground Structures during Rapid Groundwater Rise: A Critical Review

**Yijia Lin[1], Xianyun Wang[2,*], Hongtao Zhang[2], Jiaqi Yu[1], Hengyun Jiang[1]**

[1]*Brunel London School, North China University of Technology, Beijing, China*

[2]*School of Architecture and Construction, North China University of Technology, Beijing, China*

**Corresponding Author*

**Abstract: Engineers commonly regard rapidly rising groundwater levels as equivalent to static buoyancy loads on underground structures. This simplified method is valid when soil hydraulic connection is sufficient and pore water pressure becomes stable. However, it fails to reflect the actual variation of pressure boundaries during transient water-level rising processes. This paper systematically reviews existing studies on groundwater-induced structural uplift, pore water pressure transfer, soil-structure interface behavior, seepage influence, structural anti-floating capacity, field monitoring technologies and drainage control strategies. Previous studies indicate that external water levels govern the overall hydraulic system, yet they cannot directly represent the real bottom pressure of structural floors. Local pressure distribution is comprehensively affected by water connectivity, soil permeability, water storage properties, interfacial pore characteristics and historical loading conditions. Moreover, structural anti-floating resistance gradually increases with cumulative structural displacement. This study proposes four core evaluation indexes for anti-floating safety: pressure amplitude, pressure boundary condition, upward resultant force and effective structural resistance. Traditional static water pressure methods, buoyancy reduction coefficients, seepage analyses and coupled contact models are not mutually exclusive, but form a hierarchical and complementary analytical system. Finally, a complete research scheme is proposed to synchronously monitor local water pressure, seepage flow, interface parameters, force balance and structural deformation. This framework reveals how controlled drainage adjusts pressure boundaries and structural mechanical responses, providing reliable mechanical support to convert groundwater monitoring data into scientific anti-uplift decisions for underground structures.**

**Keywords: Groundwater Level Rise; Buoyancy Resistance; Hydrostatic Pressure Boundary; Soil-Structure Interaction; Interface; Uplift Resistance; Seepage Flow**

## 1. Introduction

The current problem faced by the urban shallow subsurface structure basin is the rapid rise of the groundwater level, which is a regular load rather than an abnormal one. The shallow aquifer can be replenished within a few hours under the conditions of extreme rainfall and circulation; on a longer time scale, further changes in artificial replenishment, leakage control projects, and pumping modes have reshaped the groundwater system [1,2]. We have observed that open-cut stations, public tunnels, underground garages, and large culverts will experience increasing upward demands. The standard calculation method is simple: select a groundwater level, integrate the distribution of corresponding hydrostatic pressure at the bottom of the structure, and compare the results with self-weight, permanent loads, additional loads, anchoring forces, and soil resistance. For the final state with good hydraulic connectivity and a quasi-steady state of pore pressure field, this calculation is still indispensable [3,4]. The rise itself is where the trouble starts. A groundwater level belongs to the far field; the load on a base is set locally, by the pressure field that actually reaches the soil-structure interface and by the area across which it acts. For fine-grained soil conditions, pressures acting beneath flotation-susceptible underground structures may diverge from external hydraulic head readings, a behavior supported by model-scale

experiments, field monitoring data and theoretical analyses; such pore-pressure discrepancies develop because pressure propagation proceeds across a finite time window [5-10]. Recent case studies have shown that subway construction in soft soil areas can induce coupled responses in groundwater recovery and ground deformation [11].

None of this is an argument against hydrostatics. Hydrostatic integration captures a limiting state, and it captures that state fully only when the hydraulic source is effectively linked to the interface, dissipation and redistribution of pressure have advanced far enough, and the assumed pressure boundary exists in reality. In a transient both the pressure field p(x,t) and the effective pressurized area $A_p(t)$ can move. Eq (1) can be used to calculate the final upward liquid pressure. This force separates the hydraulic actuator and the actual boundary of the applied driving load from each other. This conceptual division forms the basis for the analysis and evaluation system of this article. This paper reviews various research methods employed in existing literature to address issues such as groundwater level rise, soil-structure contact surfaces, hydraulic connectivity characteristics, seepage effects, and displacement-induced resistance. Subsequently, evidence was organized around two questions: one is how the real water pressure boundary forms beneath the embedded structure through what process; the other is how this moving boundary and the induced resistance jointly determine the stability against uplift. The article did not introduce new design coefficients. Its purpose was to clarify what can be determined by the existing calculations, in which aspects they are still overly idealized, and what elements a mechanical framework that can be verified through experiments should include.

$$U(t)=\int_{A_p(t)} p\,(\mathrm{x},t)\mathrm{d}A \tag{1}$$

## 2. Scope and Organizing Framework

### 2.1 Review Material and Mechanics-Chain Framework

This study is based on 30 selected literature and adopts a critical narrative review method instead of following the protocol of systematic review or meta-analysis workflow. The collected literature is intended to support a research proposal on the anti-floating performance of underground structures, covering review papers, laboratory and centrifuge test results, on-site measurement records, theoretical derivations, and numerical simulations that couple seepage and interface contact responses. Through cross-reference reading of these sources, the assumptions regarding hydraulic boundary conditions, contact conditions, anti-floating resistance, and intervention measures were revealed. However, due to significant differences in structural configuration, soil conditions, loading sequence, and measured response parameters, we may not be able to quantitatively integrate the experimental results or directly compare across cases.

### 2.2 Mechanics-Chain Organizing Logic

The changes in external water head; the state of the soil-structure interface; the pressure boundary and the resultant upward force it generates; as well as the structural displacement and the resisting forces mobilized are four interrelated quantities used for organizing the review. In addition, the design review classifies the factors, methods and anti-force reduction measures used in the anti-floating practice [3, 4]. The model-scale tests in clay [5] and the clay test-simulation studies based on the fitted reduction coefficients [6] indicate that the pressure acting on the base is spatially distributed and is governed by the transmission conditions. However, it should be noted that although the buoyancy reduction coefficient can reflect the system behavior obtained through calculation or experiment, a single-valued parameter cannot distinguish between partial pressure transmission and the limited pressurized interface area or the force distribution shift under seepage driving. Under the condition where the water level is rising but has not yet reached the long-term stable equilibrium level, this distinction becomes particularly crucial [3-6].

### 2.3 Definition of Key Terminology

In this article, "interface" is defined as the contact area between the soil at the bottom or side wall of the structure and the concrete, which includes the closely contacting pressure-bearing stress zone, local disengaged gaps, seepage channels controlled by the roughness of the contact surface, and retained water bodies remaining in the deformable gaps or the surrounding soil. In contrast, "pressure

boundary" specifically refers to the part of the interface that can form a hydraulic pressure field and contribute to the vertical resultant force. This pressure boundary is not equivalent to the external water table: for the same external water level, the effect on different areas of the interface varies. Figure 1 combines these definitions into the mechanics framework.

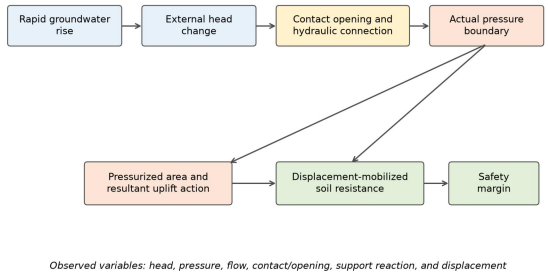



**Figure 1. Mechanical Framework to Characterise Pressure Boundary Development and Structural Anti-Flotation Response during Rapid Groundwater Level Rise**

## 3. Groundwater Level rise, Pore Pressure Transmission and Actual Pressure Boundary

### 3.1 Observations of Transient Pore-Pressure

That groundwater conditions shape both demand and resistance has been recognized within anti-flotation design for a long time. Recent reviews survey a broad spectrum of design methods, measures for reducing water pressure, and combinations of structural and geotechnical provisions [3,4]. In day-to-day practice the water level is frequently turned straight into a design pressure: it can be measured, communicated without difficulty, and it is conservative for many long-term situations. This method is very helpful, but it merely shifts the difficulty to the hypothetical boundaries: which parts of the structure bear the selected pressure, and where?

The clay model test directly provided us with a reason, and the issue was retained. Rather than treating uplift as a scalar function of groundwater level, Water pressures acting on flotation-prone structures were measured by Ren et al. [5], who showed that the spatial distribution of pressure response cannot be ignored. In clay, Sun et al. [6] investigated the issue of buoyancy reduction through a combined approach of model experiments and numerical simulations. Evidence from clay-limestone foundations also points to the same conclusion [7]: pore pressure is controlled by geological conditions and water conductivity conditions, and a uniform external water head may not reflect these conditions. Guo et al. [8] addressed how pore-water pressure is transmitted through silty clay surrounding underground structures.

Analytical and numerical studies have likewise reported pressure reduction wherever direct hydraulic transmission is hindered by a low-permeability stratum, an impervious foundation, or particular seepage conditions [9,10]. These studies establish that buoyancy responds to the seepage field and to boundary conditions. They do not settle how a pressure field reaches an actual soil-concrete interface—one whose contact state may itself shift as the structure deforms. Pressure under a base turns on more than bulk permeability: source connection, path length, local conductance, storage and the geometry of the interface that water can reach all enter in.

### 3.2 Hydraulic States and Engineering Implications

Three possible conditions can be distinguished here, although they do not necessarily follow a fixed chronological order. In some cases, the pressure front has not yet reached a given part of the interface. Or water may have reached a local region while the pressure distribution is still settling, because fluid is going into storage in the surrounding soil, in cavities or in deformable gaps. Eventually, the pressure within a connected region will converge toward the value set by the relevant boundary head. These describe hydraulics, not fixed classes of structural response; how they follow one another depends on the rise history and on the boundary as it changes.

Although it is a local phenomenon, its engineering impact is real. When the rate of water level rise is at the same time as the pressure regulation time scale of the soil-structure system, the water level should be regarded as the input condition for the boundary formation problem. To determine the actual mechanism, local pressure, flow velocity and pressure difference must be measured. Calculations based on the far-field level can still be used as a reference, but it should not hide the fact that the assumed interface pressure has indeed been established.

## 4. Mechanical Contact, Opening, and Hydraulic Connectivity

### 4.1 Distinction between Contact State and

**Hydraulic Flow**

In the current situation, although mechanical contact and hydraulic flow are related, their natures are completely different. Contact mechanics mainly controls the path of load transmission within micro-convex bodies or soil bearing areas; hydraulic connectivity depends on whether the flow channels are continuous and their conducting capacity. For instance, local openings can increase the storage space of water, but they do not necessarily form a continuous passage; conversely, even if most interfaces have undergone mechanical closure, the interconnected rough channels still have the ability to conduct water. Rough-fracture experiments make this concrete—contact area governs seepage behavior under normal stress [12], and shear of rough joints couples the evolving contact state to seepage characteristics [13]. Describing an interface only as “closed” or “open” therefore discards the very variables through which deformation feeds pressure transfer.

### 4.2 Coupled Contact-Seepage Modelling for Underground Structures

Contact-seepage formulations give structural analysis a way to carry that same principle over. Mechanically consistent fluid-structure models have now been extended to incorporate seepage analysis. Meanwhile, studies on anchors and skirted foundations have explicitly modeled the seepage effects on uplifted structures [14-16]. Such models suggest that a joint formulation is required for contact constraints and fluid flow when separation and seepage take place simultaneously. They have mostly been applied to foundations, anchors, pipelines or idealized interfaces, rather than to the pressure boundary under a long, shallow reinforced-concrete base.

For an underground structure the contact state also reflects construction defects, disturbance of the soil, uneven bedding, loading history and the way support is redistributed as uplift proceeds. Microscopic roughness parameters are therefore not necessarily the right state variables. At engineering scale, representative opening, the share of contact that bears load, pressure gradients between neighboring zones of the interface, discharge, and the phase relation between an imposed head change and the local pressure are quantities that can serve—each can be measured or inferred in a controlled model test, and together they allow a check on whether a single opening parameter suffices.

Which way the coupling runs is the issue left unresolved. Rising water pressure can encourage local separation; separation in turn enlarges storage and changes conductance. On the contrary, local contact may impede the fluid's return flow and simultaneously provide a resistance path to slow down the uplift. We have found that the mechanical framework must allow for differentially changing mechanical contact and hydraulic connectivity. Therefore, this proposition can be verified by physical experiments and does not assume that a fixed sequence must always be followed.

## 5. From Pressure Boundary to Uplift Action and Mobilized Resistance

### 5.1 Uplift Load and Displacement-Dependent Soil Resistance

The vertical stability of embedded structures is governed not by pressure itself but by the resultant force. When the free body of the embedded structure is constrained at a certain displacement, the upward hydraulic force is balanced by the self-weight of the structure, permanent surcharge, existing anchor force and resistance provided by the surrounding soil. Such resistances usually vary with displacement and can involve lateral frictional resistance, end effects, soil bulging, suction or over-pore water pressure effects, as well as progressive failure mechanisms. Therefore, safety assessment cannot be made solely based on the instantaneous state of the current pressure field; the developed displacement and corresponding resistance state must also be considered simultaneously.

Physical experiments on buried structures within sandy deposits subjected to varying water tables confirm mutual interplay between hydraulic loads and ground behaviour [17]. Additional tunnel-scale laboratory work under variable water conditions links structural feedback to such coupled mechanisms [18]. The combination of centrifugal model tests and numerical simulation of subway stations indicates that the interface friction force between soil and concrete is the dominant factor controlling uplift-related collapses [19]. The research on soft clay shield tunnels has to some extent revealed the gradually developing anti-uplift instability mode. In addition, the subsequent nonlinear calculation schemes adopt mobilized undrained shear

strength to capture the law of soil strength evolution with deformation [20,21]. A series of tests on buildings and underground silos in saturated clay show that buoyancy and lateral friction resistance are jointly affected by soil type, structural configuration, and external load conditions [22–24].

### 5.2 Path-Dependent Anti-Flotation Safety Assessment

Based on the available data, seepage acts on both sides of the force balance: numerical simulations of plate anchors [14], skirt-type foundations subjected to vertical uplift forces [15], and buried pipelines [25] indicate that the seepage force and the water flow beneath the uplift body will re-adjust the resistance mechanism and stress field. The same principle can also be applied to buried structures: even if the water pressure at specific locations remains unchanged, as the contact area under stress expands, the overall upward buoyancy will still increase. Conversely, if the stress boundary expands outward, even if the local water pressure decreases, the total upward load may not necessarily decrease.

Therefore, when conducting anti-floating safety evaluations, the impact of the load change process cannot be ignored. During the analysis, it is necessary to combine the set allowable deformation amount and the on-site hydrogeological conditions, and not just simply calculate the safety factor of the vertical resultant force at a certain instant.

This can also explain why some experiments that seem to have similar principles, but ultimately yield very different results. One cannot simply assume that if the applied external loads on two specimens are the same, their working conditions are completely the same. Their initial contact surface distribution, the process of gap opening, and the sequence of load application may all be different.

Changes in the permeability capacity of the contact surface and the storage space of water will cause the pressure boundary to develop along different paths; and different deformation histories will bring about different soil resistance. Comparing only the final result state of the tests cannot help determine which action mechanism caused the structure to float.

## 6. Modeling Strategies and Limits of Common Simplifications

### 6.1 Hierarchy of Uplift Representation Models

The leading modeling approaches can be ordered according to how much boundary information they keep. Hydrostatic formulations apply pressure loads across predefined regions; this method works for scenarios with proven hydraulic connectivity and stable equilibrium. Simulating solely with a seepage module can yield the subsurface pore pressure field, but the contact state between soil and structure is typically predefined and not iteratively updated. Contact-seepage coupled analysis allows hydraulic and mechanical boundaries to evolve simultaneously; its associated structural coupling module can further incorporate resistance controlled by soil displacement. Each modeling approach has its appropriate range of application, and a common misconception is applying simplified models to conditions where boundary conditions themselves are not yet fully defined. Table 1 summarizes the boundary information retained, typical applications, and limitations of different approaches.

The reduction factor method is widely used here because it condenses complex hydro-mechanical coupling effects into a single design parameter. Existing clay experiments and numerical results indicate that this method provides engineering reference value for scheme selection and preliminary design [5,6,24]. However, the reduction factor cannot distinguish among different physical mechanisms such as insufficient water connectivity, local confined pressure, or contact-controlled seepage pathways. This paper argues that it should be regarded as a response indicator specific to certain combinations of soil, structure, boundary, and time, rather than an inherent material property of the soil. Similarly, the fixed joint model is only applicable when the joint width is known and remains essentially constant; once uplift-induced opening occurs—precisely what the model aims to predict—the underlying assumptions become unreliable. The contact mechanics and seepage formulas established for anchoring devices and foundation skirt plates demonstrate how separation, flow and stress redistribution interact [14-16]. Likewise, we observe that the underground structure model should distinguish between geometric openings and hydraulic connection channels, and check whether they maintain a unique relationship

during loading and unloading.

### 6.2 Limitations and Validation of Numerical Approaches

The core utility of numerical analysis lies in establishing feasible mechanical models, verifying the balance between water volume and forces, and helping us select experimentally relevant conditions. It cannot, by itself, establish how a real soil–concrete interface behaves hydraulically if conductance, storage, and contact parameters have not been identified independently. If only the overall global uplift displacement as a single indicator is used for calibration, some errors will cancel each other out, and thus the problem won't be apparent. The difference here is not a distinction between the analytical method and the numerical calculation method itself, but rather a difference caused by whether the pressure boundary conditions are expressed explicitly or implicitly.

**Table 1. The Expression of Groundwater Uplift Effect and Boundary Conditions**

| Representation | Pressure boundary | Contact treatment | Principal use and limitation |
|---|---|---|---|
| Hydrostatic integration | Set over a chosen area of the structure | Mostly implicit or held fixed | Quick to apply once equilibrium is established; the transient pressurized area lies beyond its reach. |
| Buoyancy-reduction coefficient | Folded into a single response coefficient | Buried within the coefficient | Handy for comparison and design; mechanism and time dependence stay unresolved. |
| Seepage analysis | Pore-pressure field computed within the soil | Hydraulic boundary at the structure often fixed | Captures transmission through soil; interface opening and connection may simply be prescribed. |
| Coupled contact-seepage analysis | Pressure field and reachable interface free to evolve together | Mechanical contact coupled to hydraulic flow | Suited to mechanism analysis; interface relations must be identified independently and validated. |
| Coupled structural response analysis | Pressure boundary tied to the structural free body | Contact and resistance varying with displacement | Joins uplift action to mobilized resistance; force and displacement must be measured in synchrony. |

## 7. Monitoring, Drainage Control and Restoration of Anti-Floating Capacity

### 7.1 Mechanics-Driven Monitoring and Warning

The actual function of monitoring is to determine the parameters related to hydraulic load and soil resistance. If only the water level data is considered, one can only know the changes in external water load, but cannot obtain the pressure at the local contact surface, nor can the distribution range of high-pressure areas be determined. Therefore, for underground structures with the risk of rising, the monitoring plan needs to combine external and local hydraulic measurement data and structural response data, and also need to conduct a comprehensive analysis by integrating the patterns of changes in various data over time.

Using high-density strain monitoring data to diagnose the problem of tunnel rising can demonstrate the value of high spatial resolution monitoring data; while the rising analysis model can establish the relationship between structural deformation and internal forces [26,27]. To change the seepage effect, the key lies in adjusting the pressure boundary and the process of groundwater change, rather than simply lowering the nominal water level. Relevant experimental tests of defective underground structures prove that engineering control measures can change the seepage characteristics; there are also model studies that have discussed the drainage schemes when the water level rises [28,29]. The controlled backfilling project carried out for the underground garage that has already risen also indicates that formulating intervention plans cannot only focus on the water control effect, but also need to take into account the current structural status and operational constraints [30].

The controllable drainage mentioned in the text belongs to restrictive engineering measures: it can reduce the water pressure, but it cannot bring unacceptable consequences such as excessive settlement, soil erosion, and redistribution of internal forces within the structure. When evaluating the drainage effect, it is also necessary to observe local pressure, the range of

high-pressure areas, drainage flow, vertical resultant force, and changes in structural displacement. If only at a single point for drainage or opening a new drainage channel, one cannot rely solely on the water level reading to determine whether this measure is effective.

### 7.2 Mechanical Evaluation of Controlled Drainage

A truly effective early warning system doesn't necessarily have to calculate a very complex and incomprehensible prediction score. It can be something that we can directly observe or measure with our eyes or instruments before the water level rises. The drainage regulation mentioned here is a controllable approach: it is used to reduce the load brought by water, without causing excessive hydraulic gradients, soil erosion, or dangerous changes in the structural load. Laboratory tests on defective underground structures show that control measures alter seepage interaction [28], similar-model studies of subway stations examine diversion measures during groundwater rise [29], and the controlled lowering of a raised underground garage shows that intervention must be weighed against structural and operational state [30].

## 8. Research Gaps and a Forward Mechanics Agenda

### 8.1 Identified Research Gaps

The literature reviewed here gives anti-flotation analysis a solid foundation, yet four connected gaps persist. Studies of water pressure tend to resolve either the far-field seepage field or the structural resultant; the evolving pressure boundary at a deformable soil-concrete interface is identified directly far less often. Work on interfaces demonstrates how much contact distribution matters hydraulically, but those lessons have not regularly been converted into observables for buried reinforced-concrete bases. Studies of uplift resistance lay out important failure and resistance mechanisms, but pressure growth, growth of the pressurized area and the mobilization of resistance are seldom separated within a single synchronized free-body analysis. Monitoring and drainage work, finally, offers valuable tools for response and intervention whose use as indicators of boundary formation constrained by mechanics remains limited [5,12-21,25-30].

### 8.2 Experimental-Numerical Research Outlook

A focused program of experiments can close these gaps without turning each process into a research theme of its own. Firstly, during the controlled process of water head variation, measure what the gap opening looks like, and how the contact area is distributed; at the same time, record the water discharge capacity, water storage characteristics, and how the local pressure changes throughout the opening-closing process. The second is to take matched physical specimens through prescribed displacement or load paths and trace how the moving pressure boundary alters both the uplift resultant and the resistance mobilized. Among all the relevant studies, the most crucial aspect is that all the measurement data must be independently measured. Local water pressure, water flow rate, vertical resultant force, and structural displacement must all be directly measured and cannot be estimated or guessed based on other data.

The purpose of numerical simulation is to assist in explaining the problem, rather than replacing real experiments. Through seepage numerical calculations, we can analyze whether structural gaps will open and whether water bodies will be connected at different time periods, check whether the system remains balanced and whether water volume is conserved, and also distinguish the differences in the force mechanism corresponding to different water head changes. However, the numerical model can only perform analysis. The real soil and concrete structure still need to be verified through physical experiments to determine which laws they follow and what ranges of parameters are applicable. Distinguishing the roles of the two will prevent mistakenly taking the boundary assumptions in the software as conclusions drawn from real experiments.

In addition, the research also pays special attention to the differences in size scales. Small-scale tabletop experiments and conventional laboratory tests are suitable for observing the laws of the interaction between water and soil, and can also measure the critical values at which structural changes occur. However, the small models in the laboratory cannot replicate all the conditions of the real site, such as long-term change processes, in-situ soil stress, and the true stiffness of the structure. Therefore, when

applying the results of small-scale model tests to actual engineering, the degree of gap opening, effective contact area, duration of water level rise, duration of pressure changes, as well as the actual stress and structural stiffness conditions at the site must be considered. What is involved is a mechanics transfer problem, not a straightforward exercise in geometric scaling.

## 9. Cross-Cutting Mechanics Lessons from Adjacent Evidence

### 9.1 Theoretical Basis and Related-Field Insights

The pressure-boundary problem originates in Biot's coupled consolidation and effective-stress framework, in which solid deformation and pore-pressure change advance together and both force balance and water continuity must hold [31]. Later fluid–structure-contact formulations extend that coupling to interfaces whose mechanical and hydraulic boundaries can change simultaneously, first for rough-surface porous contact [32] and general fluid–structure-contact problems [33], then in analytical treatments [34] and unified fluid–porous–structure-contact formulations [35]. Fracture-flow studies reach the same conclusion at smaller scale: mesoscopic deformation changes contact area and hydraulic aperture [36], and three-dimensional rough-walled fractures show that surface contact mode, not a single aperture, controls flow [37]. Segment-uplift analyses in shield tunnelling further show that seepage in the water-bearing ground cannot always be separated from structural response [38]. These works reinforce the case for interface variables that can be observed directly in anti-flotation research, while the differences among rock fractures, segmental linings and a soil-concrete base should be kept in view.

We were inspired by the phenomena observed from earthquakes and soil liquefaction, but the lessons they convey are not exactly the same. The vibration table and centrifuge have conducted numerous tests on tunnels and buried pipelines. The results show that the extent to which the foundation is disturbed and becomes softer, as well as the resulting structural displacement and the proportion of the overall vertical force, are equally crucial [39-42]. Studies of tunnel support under displacement imposed by faults show in much the same way how a shifting ground constraint redistributes structural action [43]. The rise of groundwater level does not cause the supporting soil layer to liquefy, so the destruction mechanism of liquefaction cannot be directly applied to explain this situation. Even so, this comparison still tells us: when making an assessment, we should pay more attention to the affected area, how the supporting force is redistributed, and the actual displacement of the structure, rather than just relying on a certain standardized force ratio for judgment.

Anti-uplift piles add one more point of reference on the resistance side. Model tests and field benchmarking of belled uplift piles under changing groundwater tie growing immersion to falling effective stress, to redistribution of interface resistance and to an altered load-displacement response [44]. The result sits with the wider conclusion of this review: an anti-flotation check should pin down the hydraulic action and the mobilized resistance together, rather than holding one fixed in assumption while the other moves.

### 9.2 Implications for Monitoring and Anti-Flotation Design

The monitoring literature likewise separates the gathering of data from its mechanical reading. Structural health monitoring is commonly cast as the task of spotting meaningful changes in material properties, geometry, boundary conditions or connectivity [45]. Bayesian updating and dynamic probabilistic models offer established means of revising a model in the light of observations, observations made under environmental variation included [46-48], and recent tunnel applications bear out the promise of data-driven uplift prediction from field data [49]. The phenomenon of rapid groundwater rise is still very valuable for indicators that take into account mechanical constraints. It is a tangible quantity that can be used for practical judgment: as long as it issues a warning, it corresponds to the actual observable pressure transmission, structural stress, and displacement, rather than just the spurious correlations derived from statistical data. Existing utility-tunnel provisions keep their place for structural configuration and design context; the transient taking shape of the actual pressure boundary is what calls for an explicit hydraulic-mechanical reading [50].

## 10. Conclusions

Fast-moving groundwater surges supply

hydraulic forcing from outside buried constructions, yet external water readings cannot directly set transient base pressures. The actual uplift deformation of the structure is the result of the combined effect of local pressure changes and the influence range of water load. At the same time, the deformation characteristics of the contact surface between the soil and concrete also need to be analyzed and discussed separately from the hydraulic connectivity indicators. Bearing contact zones, physical gaps, leftover flow pathways, water storage and source linkage may progress simultaneously without sharing identical development timelines. The distinction gives a physical footing for reading pressure-transfer delays and water action that is uneven across space.

Where the pressure boundary and soil resistance take shape in the course of uplift, anti-flotation safety is path dependent. Firstly, the pressure amplitude, the area subjected to pressure, and the displacement resistance should be calculated separately. Then, in combination with the specific hydraulic conditions and the allowable displacement limit, the structural safety margin should be comprehensively calculated. The static water integration method, the reduction coefficient method, the seepage analysis and the contact coupling model belong to a complementary analysis system. The model selection should be based on whether the assumed pressure boundary truly matches the on-site groundwater conditions and the structural stress state.

The preliminary research needs to integrate local water flow monitoring, contact surface response observation, overall force balance calculation, structural displacement analysis and mechanical drainage evaluation to construct an integrated analysis framework. This system can achieve the organic combination of groundwater monitoring and anti-floating safety decision-making, breaking through the traditional single evaluation mode that solely relies on water level thresholds to determine risks.

## References

[1] Zhao D, Xu H, Li Y, et al. Locally opposite responses of the 2023 Beijing-Tianjin-Hebei extreme rainfall event to global anthropogenic warming. npj Climate and Atmospheric Science, 2024, 7: 38. https://doi.org/10.1038/s41612-024-00584-7.

[2] Guo H, Hu W, Yang C, Wan F. Moisture sources and atmospheric circulation patterns for extreme rainfall event over North China Plain from 29 July to 2 August 2023. Earth and Space Science, 2024, 11(12): e2024EA003956. https://doi.org/10.1029/2024EA003956.

[3] Wang S, Dong S, Huang Y, Song Z, Wu T, Zheng S. Research progress in anti-flotation design of underground structures. Journal of Yangtze River Scientific Research Institute, 2025, 42(6): 154-161. https://doi.org/10.11988/ckyyb.20240480.

[4] Yang M, Fu X, Liu H, Wang L, Li Q. Influencing factors, design methods, and buoyancy reduction measures for basement anti-flotation engineering. Buildings, 2024, 14(9): 3005. https://doi.org/10.3390/buildings14093005.

[5] Ren Z, Lu Q, Liu K, Ni P, Mei G. Model-scale tests to examine water pressures acting on potentially buoyant underground structures in clay strata. Journal of Rock Mechanics and Geotechnical Engineering, 2022, 14(3): 861-872. https://doi.org/10.1016/j.jrmge.2021.09.014.

[6] Sun W, Liu H, Zhang W, Liu S, Han L. Determination of groundwater buoyancy reduction coefficient in clay: Model tests, numerical simulations and machine learning methods. Underground Space, 2023, 13: 228-240. https://doi.org/10.1016/j.undsp.2023.06.001.

[7] Song L, Zheng G, Yang T, Zhang J, Li Z, Mei G. Field tests and analysis of pore pressure in clay-limestone foundations. Chinese Journal of Geotechnical Engineering, 2026, 48(5): 1092-1100. https://doi.org/10.11779/CJGE20250225.

[8] Guo H, Zhou R, Sun C, Lin Y, Xie J. Buoyancy of underground structures and pore water pressure conduction law in silty clay strata. Heliyon, 2024, 10(1): e24256. https://doi.org/10.1016/j.heliyon.2024.e24256.

[9] Zhou J, Lin C, Chen C, Zhao X. Reduction of groundwater buoyancy on the basement in weak-permeable/impervious foundations. Advances in Civil Engineering, 2019, 2019: 7826513. https://doi.org/10.1155/2019/7672930.

[10] Zhang J, Cao J, Mu L, Wang L, Li J. Buoyancy force acting on underground structures considering seepage of confined

water. Complexity, 2019, 2019: 7672930. https://doi.org/10.1155/2019/7672930.

[11] Yang J, Wu H, Yang X, Zhou S, Guo D, Chen R. Land uplift induced by groundwater rise in thick deep soft clay strata and its impact on metro tunnels: A case study from Tianjin in China. Natural Hazards, 2026, 122(6): 265. https://doi.org/10.1007/s11069-026-07995-0.

[12]Li M, Liu X, Li Y, Hou Z, Qiao S. Effect of contact areas on seepage behavior in rough fractures under normal stress. International Journal of Geomechanics, 2022, 22(4): 04022019. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002330.

[13]Yao C, Sun Z, Jin Y, He C, Yang J, Zhang X, Zhou C. Evolution of contact state during shear of rough rock joints and its influence on seepage characteristics. International Journal of Geomechanics, 2022, 22(12): 04022214. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002558.

[14]Maitra S, White D, Chatterjee S, Choudhury D. Numerical modelling of seepage and tension beneath plate anchors. Computers and Geotechnics, 2019, 108: 131-142. https://doi.org/10.1016/j.compgeo.2018.12.022.

[15]Mana D S K, Gourvenec S, Randolph M F. Numerical modelling of seepage beneath skirted foundations subjected to vertical uplift. Computers and Geotechnics, 2014, 55: 150-157. https://doi.org/10.1016/j.compgeo.2013.08.007.

[16]Burman E, Fernandez M A, Frei S, Gerosa F M. A mechanically consistent model for fluid-structure interactions with contact including seepage. Computer Methods in Applied Mechanics and Engineering, 2022, 392: 114637. https://doi.org/10.1016/j.cma.2022.114637.

[17]Liu H, Sun W, Zhang Y, Zhang W, Han F, Su W. Experimental analysis on the interaction between underground structures and sand layer under groundwater level change. Underground Space, 2023, 10: 15-36. https://doi.org/10.1016/j.undsp.2022.08.006.

[18]Sun W, Han F, Zhang Y, Zhang W, Zhang R, Su W. Experimental assessment of structural responses of tunnels under the groundwater level fluctuation. Tunnelling and Underground Space Technology, 2023, 137: 105138. https://doi.org/10.1016/j.tust.2023.105138.

[19]Wang Y, Yu S, Yin P, Zhang X, Hu J, Pan D, Chen Z. Impact of rising groundwater level on uplift behavior of subway stations considering soil-structure interface friction: Centrifuge and numerical investigation. Tunnelling and Underground Space Technology, 2026, 177: 107944. https://doi.org/10.1016/j.tust.2026.107944.

[20]Gong Q, Zhao Y, Zhou J, Zhou S. Uplift resistance and progressive failure mechanisms of metro shield tunnel in soft clay. Tunnelling and Underground Space Technology, 2018, 82: 222-234. https://doi.org/10.1016/j.tust.2018.08.038.

[21]Chen H, Zhang D M, Bai H, Zhang J Z, Huang H W. Nonlinear uplift resistance solution for a buoyant tunnel considering mobilized undrained shear strength under groundwater rise. Tunnelling and Underground Space Technology, 2026, 174: 107653. https://doi.org/10.1016/j.tust.2026.107653.

[22]Fan Z, Xu C, Yang K, Xue X, Zeng C. Experimental study on the influence of rising water levels on the buoyancy of building structure. Water, 2025, 17(9): 1377. https://doi.org/10.3390/w17091377.

[23]Yang B, Chen S, Zhang C, Su N, Zhang S, Zhu D. Experimental study on buoyancy and side friction of underground silos in sand and silty clay. Frontiers in Earth Science, 2025, 13: 1698922. https://doi.org/10.3389/feart.2025.1698922.

[24]Gao T, Xu Y, Zhou X, Wang Y, Liu H. Experimental and theoretical evaluation of buoyancy reduction in saturated clay soils. Water, 2025, 17(12): 1832. https://doi.org/10.3390/w17121832.

[25]Maitra S, Chatterjee S, White D, Choudhury D. Uplift resistance of buried pipelines: The contribution of seepage forces. Ocean Engineering, 2022, 250: 111037. https://doi.org/10.1016/j.oceaneng.2022.111037.

[26] Chen T, Chen R P, Cheng H Z, Hou P B, Meng F Y. Analytical method for tunnel deformation and internal forces during uplift. Tunnelling and Underground Space Technology, 2026, 170: 107387.

https://doi.org/10.1016/j.tust.2025.107387.

[27]Ma X, Xu Q, Liu Y. Diagnosis method for the structural uplift of a water-rich shield tunnel based on the spatiotemporal characteristics of the densely distributed strain data. Computer-Aided Civil and Infrastructure Engineering, 2025, 40(30): 6067-6088. https://doi.org/10.1111/mice.70137.

[28]Peng S, Li C, Luo G, Li Y, Pan H, Cao H, Liang S. Laboratory investigation effects of control measures for leakage-induced erosion on seepage interactions in defective underground structures. Tunnelling and Underground Space Technology, 2025, 161: 106593. https://doi.org/10.1016/j.tust.2025.106593.

[29]Huang Y, Gao Y, Li H, Men Y, Hu T. Application research on groundwater-level rise and diversion measures in subway station operation period via similar physical models. Frontiers in Water, 2026, 8: 1774808. https://doi.org/10.3389/frwa.2026.1774808.

[30]Cas B, Sporin J. Buoyancy effects on structures: A case study on the controlled lowering of a raised underground garage. Structures, 2025, 71: 108121. https://doi.org/10.1016/j.istruc.2024.108121.

[31]Biot M A. General theory of three-dimensional consolidation. Journal of Applied Physics, 1941, 12(2): 155-164. https://doi.org/10.1063/1.1712886.

[32]Ager C, Schott B, Vuong A-T, Popp A, Wall W A. A consistent approach for fluid-structure-contact interaction based on a porous flow model for rough surface contact. International Journal for Numerical Methods in Engineering, 2019, 119(13): 1345-1378. https://doi.org/10.1002/nme.6094.

[33]Ager C, Seitz A, Wall W A. A consistent and versatile computational approach for general fluid-structure-contact interaction problems. International Journal for Numerical Methods in Engineering, 2021, 122(19): 5279-5312. https://doi.org/10.1002/nme.6556.

[34]Champion M, Fernandez M A, Grandmont C, Vergnet F, Vidrascu M. On the analysis of a mechanically consistent model of fluid-structure-contact interaction. Mathematics in Engineering, 2024, 6(3): 425-467. https://doi.org/10.3934/mine.2024018.

[35]Gerosa F M, Marsden A L. A mechanically consistent unified formulation for fluid-porous-structure-contact interaction. Computer Methods in Applied Mechanics and Engineering, 2024, 425: 116942. https://doi.org/10.1016/j.cma.2024.116942.

[36]Han C, Bai Y, Zhang W, Zhang J, Ma H, Li W. Numerical investigation on the influence of mesoscopic deformation on contact area and hydraulic aperture to fracture seepage. Deep Underground Science and Engineering, 2026, 5(2): 567-580. https://doi.org/10.1002/dug2.70028.

[37]Zheng J, Jin Y, Li Z, Zhao M, Dong J, Lu Y, Wang Z, Liu G. Effects of surface contact mode on fluid flow through three-dimensional rough-walled rock fractures with contact areas. Physics of Fluids, 2026, 38(3): 033611. https://doi.org/10.1063/5.0314338.

[38]Guo J, Li Z, Liu J, Wu S, Li H, Shi S, Ye Q, Wang X. Analysis of segment uplift during shield tunnel construction considering stratum seepage effects. Scientific Reports, 2026, 16(1): 14501. https://doi.org/10.1038/s41598-026-44530-4.

[39]Watanabe K, Sawada R, Koseki J. Uplift mechanism of open-cut tunnel in liquefied ground and simplified method to evaluate the stability against uplifting. Soils and Foundations, 2016, 56(3): 412-426. https://doi.org/10.1016/j.sandf.2016.04.004.

[40]Zhang H, Zhao Y, Gao M. Seismic sequence effects on buried pipelines crossing nonuniform sites with ground settlement by dynamic centrifuge test. Advances in Civil Engineering, 2022, 2022: 1133036. https://doi.org/10.1155/2022/1133036.

[41]Zhang H, Zhao Y, Gao M, Gao J. Centrifugal seismic experimental study of buried pipelines in non-uniform soil. Engineering Mechanics, 2021, 38(11): 88-94. https://doi.org/10.6052/j.issn.1000-4750.2020.10.0747.

[42]Zhang X, Ji Z, Huang K, Wang Z, Gao H, Hu Z. Study on uplift mechanism and anti-uplift measures of shallow-buried utility tunnels in liquefiable soils. Chinese Journal of Rock Mechanics and Engineering, 2024, 43(2): 510-520.

[43]Zhang H, Zhao Y, Gao M, Gao J. Study on mechanical properties of corrugated steel

support tunnel under fault sliding. Engineering Computations, 2023, 40(9/10): 3116-3135.

[44]Li H, Li Y, Yao A, Gong Y. Immersion ratio-driven degradation and load upshift of belled uplift piles under groundwater effects: Model tests, field benchmark, and design relations. Journal of Geotechnical and Geoenvironmental Engineering, 2026, 152(9). https://doi.org/10.1061/JGGEFK.GTENG-15001.

[45]Farrar C R, Worden K. An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A, 2007, 365: 303-315. https://doi.org/10.1098/rsta.2006.1928.

[46]Beck J L, Katafygiotis L S. Updating models and their uncertainties. I: Bayesian statistical framework. Journal of Engineering Mechanics, 1998, 124(4): 455-461. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:4(455).

[47]Straub D. Stochastic modeling of deterioration processes through dynamic Bayesian networks. Journal of Engineering Mechanics, 2009, 135(10): 1089-1099. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000024.

[48]Simon P, Schneider R, Baessler M, Morgenthal G. A Bayesian probabilistic framework for building models for structural health monitoring of structures subject to environmental variability. Structural Control and Health Monitoring, 2024, 2024: 4204316. https://doi.org/10.1155/2024/4204316.

[49]Wu H, Shen S-L, Zhou A, Lyu H-M. Bayesian graph attention network for segment uplift prediction in shield tunnelling. Tunnelling and Underground Space Technology, 2026, 178: 108034.

[50]Ministry of Housing and Urban-Rural Development of the People's Republic of China. Technical Standard for Urban Utility Tunnel Engineering: GB/T 50838-2015 (2024 partial revision). Beijing, China, 2024.