Evaluation of the Effectiveness about Hydrostatic Pressure Relief Technology for Structures at Mountainous Terrains

YanSheng Chang1*, MingShu Lee2

1 College of Civil Engineering, Putian University, Putian City, Fujian Province, 351100, China
2 CUC Engineering Consultant, New Taipei City, Taiwan Province, 231, Taiwan China

* 1444351479@qq.com

Abstract. The subdivision and development of the mountain terrain is formed under the condition of geological, soil water conservation, foundation buoyancy and lateral seepage pressure caused by the groundwater. This issue is exacerbated by global warming and environmental change. The unpredictable nature of underground water fluctuation can have detrimental effects on the quality of underground infrastructure, and often reduces the functional viability of basement space in a building. The effects of groundwater on the structural stability must be carefully evaluated and analysed during the planning stage before construction. Proper mitigation measures must be developed to prevent any possible structural damage or basement leakage. Practical construction experiences and figures show that the use of drainage and anti-floating method "Hydrostatic Pressure Relief technology (HPR)" can effectively control the encountered groundwater problems for subdivision and development at mountainous terrains. It is also valid to impede basement sidewall leakage and capable of serving as an effective means of damp proofing. The relief of hydrostatic pressure through a water distribution system makes underground spaces more resilient and adaptable, thus reducing their vulnerability to future climate changes.

1. Introduction

The rapid development of city with limited land resources accelerated the trend of urbanization in mountain. Modern hillside buildings usually have deep basements used as parking lots, underground shopping malls or public spaces. However, it will inevitably suffer from short, medium and long-term unbalanced lateral buoyancy and water pressure on the impact of water pressure, therefore, structural design must be considered carefully to avoid long-term exposure to moisture, leakage, structural damage and other problems [1] [2].

Traditional design can overcome the problems of hillside stability and structural safety according to laws, regulations and designer's experience. However, the prevention and control of groundwater pressure in purpose of stable water flow, waterproof and leak-plugging methods often consume huge engineering resources, but still cannot guarantee the safety and comfort levels’ long-term use of the structure. The use of basement structure often appears wall cracks and seepage water abound shortly after the completion of construction. [3] [4] [5] Therefore, a permanent solution to the anti-floating seepage prevention of hillside structures should be an important design issue.

In this paper, the use of the drainage anti-flooding technology as a permanent solution for the problem is discussed and its effectiveness is assessed with the case of a 12-storey ground and 3-storey
underground building foundation at the hillside of Taiwan Taipei Naihu district, supported with practical experience as a reference for all fields.

2. Foundation structure and stratigraphic structure

2.1 Foundation structure

The foundation is located on the edge of a hillside with a long strip-shaped distribution and great terrain changes. The structure of two-storey reinforced concrete and floor design divided into four categories: 0F / 3B, 1F / 3B, 11F / 3B and 12F / 3B. Structural properties of the project are as follows:

(1) The open ground floor shared by two-storey reinforced concrete, composed of 11 floors and 12 floors respectively.

(2) Parking is available on all three-basement levels, excavation depth of approximately GL-11.3m.

(3) The structure design as caisson type foundation.

(4) Enveloping structure adopts the retaining pile to cooperate with the rotary jetting pile as the diaphragm wall.

2.2 Stratigraphic Structure and Groundwater Level

2.2.1 Overview of the Stratigraphic Structure

The geological conditions of the stratigraphic can be divided into three levels: backfill, sandy silt weathered rock block, and rock disk. The foundation of the structure falls on the third layer of gray sandstone shale interbred. The relevant formation parameters are shown in Table 1.

Table 1. The relevant formation parameters.

| Stratigraphic description (Thickness) | Classification | N Value | γ’ t/m³ | Total stress | Effective stress | Compression properties | Undrained shear strength Su t/m² |
|-------------------------------------|----------------|---------|----------|--------------|-----------------|------------------------|----------------------------------|
|                                     |                |         |          | C t/m² | φ degree | C’ t/m² | φ’ degree | Cc | Cr |
| 1. Backfill, Clay, Silt, Weathered rock. (0.7~6.1M) | SF | 3~6 (4) | 1.98 | 1.5 | 20 | 0 | 30 | 0.17 | 0.02 | — |
| 2. Yellow-brown silty sand, Sandy silt weathered sandstone blocks. (0~3.3M) | SM | 4~26 (11) | 2.01 | — | — | 0 | 32 | — | — | — |
| 3. Gary sandstone, Sand shale. (>14M) | SS/SH | >50 (50) | 2.2 | — | — | Cp | φp | Cr | φr | qu |
|                                      |                |         |         | 10 | 32 | 3 | 30 | 150~388 (250) |

2.2.2 Groundwater level

(1) The groundwater level is analysed by GL -1.5 m.

(2) Considering the change of groundwater level caused by long-term seasonal variation, the design of anti-floating water level is analysed by GL ± 0.0 m.

(3) The rock quality designation (ROD) between the degree of jointing and fracture in the rock mask is between 30 to 80. When continuous heavy rain is considered, the surface water infiltrated into the surrounding hillside can be connected to the excavation surface through the joint surface of the rock plate. The groundwater level can be coordinate with the high level of the adjacent slope, using GL+7 m for analysis.
3. The impact of groundwater on the structure

3.1 The formation of groundwater pressure approach

The base is located on the edge of a hillside. Groundwater affects the structure as shown in Figure 1. The reasons may exist separately or in combination and are respectively described as follows:

1. Surface submersion infiltration below the foundation to form buoyancy.
2. Under pressure water infiltration under the foundation to the formation of buoyancy.
3. The infiltration of runoff water at the interface of soil and rock often infiltrated to the side wall and foundation below, resulting in lateral water pressure and basal water buoyancy.
4. During the heavy rains, the infiltration of surface water on the slope slopes to the side wall of the structure and under the foundation, resulting in lateral water pressure and buoyancy of the foundation.
5. During the heavy rains, the infiltration of surface water infiltrated into the rock slope interface and formation joints, and runoff to the side wall and foundation, resulting in lateral water pressure and basal water buoyancy.
6. Water curtain imperfections or the formation of deteriorating weakness after long-term use, along the weak surface infiltration into the substrate to form water buoyancy.

![Figure 1. Schematic representation of groundwater pressure.](image)

3.2 Seepage flow and mechanical properties analysis

According to the possible formation of groundwater, with the base of structural properties, formation properties and topographic conditions, the use of two sets of cross-section data of normal and heavy rain water level shown in Figure 2.

1. Analysis of groundwater seepage: basal seepage flow analysis, sidewall infiltration analysis and infiltration analysis of surface water during heavy rainfall.
2. Groundwater pressure and stress analysis of the substrate: basal water pressure and side wall water pressure analysis during regular and heavy rain.
Table 2. Statistical analysis of the results

| Item                                           | Mode       | Normal water level analysis | Slope water level analysis |
|------------------------------------------------|------------|----------------------------|----------------------------|
| Estimate the maximum foundation permeable volume (m³/day) |            | 6.98                       | 10.60                      |
| Estimate the maximum lateral infiltration (m³/day) |            | 93.38                      | 186.77                     |
| Estimate the maximum rainfall infiltration (m³/day) |            | 0                          | 85.58                      |
| The largest substrate withstands buoyancy (T/m²) |            | 5.4                        | 12.4                       |
| Maximum foundation water pressure (T/m²)       |            | 11.3                       | 18.3                       |
| Side wall maximum water pressure (T/m²)        |            | 11.3                       | 18.3                       |
| Lowermost basement floor leaks wet due to buoyancy |            | It may happen              | It may happen              |
| Side wall seepage and deformation              |            | It may happen              | It may happen              |

3.3 The damage of groundwater on the structure

Based on the above analysis results, it is found that during the continuous heavy rain, when underground water penetration is greater than seepage permeability, underground water level will rise to the surface and water pressure increase to upper slope in a short period of time (shown in Figure 3). The rapidly increase of water penetration to sidewalls and foundation may cause structural centre of gravity and buoyancy deviation, foundation cracks, damp basement, steel corrosion and side slope...
deformation. In addition, the long term use of high groundwater pressure applied on foundation slap will cause seepage.

The base cause’s damp basement leakage is mainly due to the following:
(1) Adopting the non-watertight retaining pile to cooperate with the diaphragm wall grouting between piles, it still has the potential of infiltration of groundwater for a long time.
(2) The interface of the rock formation forms a concave shape, which shows the distribution of the rock formation in the slope saddle and the groundwater flow.
(3) The RQD of the excavation is about 30 to 80, and there are some joints.
(4) Under the condition of GL-6.0m, the disk-rock joints show the brown-gravy rust stains which have the effect of seepage water for a long time. The basal elevation rock disk has high water content and poorly barrier effect to groundwater.
(5) The part of overburden on the bottom of the foundation, the side wall of the basement and the stratum interface will form a continuous seepage passageway between the earth and rock connecting faces on the outer slope.
(6) On the side slopes, the reservoirs for water resources have relatively high elevation with the foundation of the structure, and when continuous rainfall occurs, the groundwater head height at the connecting face of earth and rock extends to the upper slope, forming a great head pressure.

Figure 3. Groundwater impact on the structure diagram

The potential harm caused by groundwater pressure and the hidden dangers of long-term disasters as assessed by this structure are as follows:
(1) When the upper load is small during the construction of the basement, continuous buoyancy and head pressure above the ground surface will cause the buoyancy of the basement too large and unbalanced, resulting in the lifting of the foundation or the buoyancy failure of the basement structure.
(2) Foundation structural water seepage pressure.
(3) Secondary foundation structural water seepage pressure.
(4) Lowest level of basement sidewall’s water seepage pressure.
(5) The long-term effect of lateral hydraulic pressure on the side wall of the basement, resulting in leakage of moisture and mottled walls.
(6) Basement wet, high humidity, poor air quality.
(7) Water seepage and dampness of long-term substrates and side walls will cause corrosion of steel bars and deterioration of concrete, drastically reduce hidden dangers on the service life and safety and disaster prevention of structures.
4. Drainage anti-floating technology applications

4.1 Hydrostatic pressure relief technology

In view of the harm that this structure faces to the groundwater; the effects of unbalanced buoyancy of foundation water, the influence of side wall water pressure on structure, the influence of seepage water on basement and side wall, etc.. Drainage anti-floating technology can permanently solve the hillside structure anti-floating anti-seepage problems. The basic idea of drainage anti-floating technology is to construct artificial drainage layer on the base of structural objects. Utilizing the characteristics of low permeability foundation, the groundwater is introduced into the base tank through the catchment and outlet system in a natural overflow manner to reduce the groundwater buoyancy and make the base water pressure maintain stable engineering skills. [6]

The structure of the “Hydrostatic Pressure Relief technology (HPR) “to reduce the buoyancy of groundwater is a new type of drainage anti-floating technology. A complete HPR system consists of four major parts: the filter layer, the ground water catchment network, the discharge system, and the seepage pressure monitoring apparatus. [7] [8] As it shown in Figure 4, the basic principle is based on the bottom of the framework of the filter, conduit water, with permanent function during the service life of the structure. To make use of the water-permeable characteristics of the low permeability layer (soil layer or rock layer) under the foundation, the accumulated static water pressure is converted into a dynamic seepage pressure, and the pressure water seepage to the substrate is naturally flooded, filtered and pooled. Then discharged through an air-tight water collecting system and a water outlet system that can control the head pressure of the substrate to structure foundation waste water pool or special water tank. Moreover, the structure of its own waste water discharge system to exclude or combined with the water recovery system reuse.

Figure 4. Schematic diagram of a Hydrostatic Pressure Relief System.

When the ability to exclude water from the foundation is much greater than the groundwater infiltrating into the foundation, the foundation will not form excess water pressure that meets the purpose of controlling the water buoyancy under the foundation floor design. Because HPR is applied to low permeable formations and the natural overflow method is used to exclude groundwater pressure, it is not forced precipitation. Therefore, it does not cause large-scale or long-range impacts on the relief surface of groundwater level at the periphery of the base. [9]
This method has the function of fully controlling the buoyancy of groundwater, preventing the leakage of construction joints and cracks in the substrate in an all-round way, also can partially change the underground hydraulic gradient at the outer side of the enclosure structure. In addition, providing effective technical support for impermeability and moisture-proof of the basement wall. In particular, the hillside structure is more equipped with the function of reducing and controlling the water pressure of the basement in a balanced manner to ensure that the basement and side wall reinforcement, concrete are not corroded and deteriorated, and also provide effective support for the disaster prevention benefits of hillside structures. Overall, this method is in line with the goal of improving the construction and long-term safety of structures, reducing construction costs and long-term maintenance costs, and is a relatively economical, time-saving, reliable and safe system method. [10]

The related design features are shown in Table 3.

Table 3. Hydrostatic Pressure Relief Layer technology design characteristics

| Workmanship design       | Design features                                                                 |
|--------------------------|---------------------------------------------------------------------------------|
| Basic mode               | Superconducting water-tight design                                             |
| Permeable system         | A high permeability retention filter layer                                      |
| Conduit system           | 7mm superconducting water grid layer                                            |
| Catchment system         | Perforated rate> 2% PVC pipe external coating of two high permeability retention filter layer |
| Outlet system            | Patented gas-tight water outlet system (including underground gas from the natural exhaust valve) |
| Isolate the system       | High-stretch plastic layer                                                      |
| Backwash system          | About 2000m2 a backwash and basement pressure observation hole                  |
| Applicable conditions    | Can be used for a long time in the higher water table, the substrate to withstand greater buoyancy conditions |
| Design changes           | Set in the substrate without changing                                           |
| Influence of formation bearing capacity | No effect                                                                       |
| Long-term use            | Can be used for a long time                                                     |
| Applicable construction conditions | New structure can be used                                                        |

4.2 Engineering benefits analysis

In order to clarify the engineering benefits of this structure, the basal water buoyancy and sidewall water pressure before and after decompression of the substrate, the regular and heavy rains were analysed, and the groundwater table was calculated by Sichart Method and Hyperbolic model, [11] [12] the influence range and the discharge of water level. At the same time, the finite element simulation model is used to carry out the graphical analysis of the groundwater pressure gradient. [13] [14] The correlation analysis and comparison results are shown in Table 4 and Figure 5, Figure 6 and Figure 7.

Table 4. Comparison of engineering benefits before and after using "Hydrostatic Pressure Relief Layer technology" for the structure

| Item                          | Normal water level analysis | Long-term water level analysis | Retaining row of piles with Water stop grouting | Rain when the water level analysis | Retaining row of piles with Water stop grouting |
|-------------------------------|----------------------------|-------------------------------|-----------------------------------------------|-----------------------------------|-----------------------------------------------|
|                                      | Before decompression | After decompression |
|--------------------------------------|----------------------|---------------------|
| largest substrate withstands (T/m²) | 5.4                  | 12.4                |
| buoyancy (Pressure control)          | 0.0                  | 0.0 (Pressure control) |
| maximum base water pressure (T/m²)   | 11.3                 | 18.3                |
| maximum base water pressure (T/m²)   | 1.5                  | 1.5                 |
| side wall maximum water pressure (T/m²) | 11.3                 | 18.3                |
| side wall maximum water pressure (T/m²) | 1.5                  | 1.5                 |
| Decompression caused by               | 3.54                 | -                   |
| external water level range (m)        |                      |                     |
| Decompression caused by               | 0.0012               | -                   |
| external water level discharge (50cm distance discharge height; m) |                      |                     |
| Lowermost basement floor leaks wet due to buoyancy | Does not happen | Does not happen |
| side wall seepage and deformation     | significantly reduce  | significantly reduce |

Figure 5. The base structure represents the cross-section finite element model.
5. Engineering system design and comprehensive benefits

5.1 Engineering system design

The structure of the groundwater pressure suffered by the impact of two main categories:

1. The foundation plate due to buoyancy caused by the destruction or floating phenomenon.
2. The basement sidewall due to water pressure caused by water seepage, wet or deformation and so on.

According to the groundwater seepage analysis, the maximum water level is designed to estimate that the maximum possible infiltration of groundwater in this base is about 100.36 m³/day, of which the maximum water seepage at the periphery and side walls of the basement is about 97.88 m³/day. Continuous heavy rain, the base of the maximum possible infiltration of groundwater about 282.94 m³/day, of which the perimeter of the basement and sidewall maximum seepage of about 279.17 m³/day.

Based on the analysis results, it can be found that after laying the hydrostatic pressure relief layer completely on the substrate, the buoyancy of groundwater can completely prevent the structural damage, moisture and seepage caused by the foundation of the structure, and maintain the permanent equilibrium of the water pressure of the substrate. Water pressure can also be drastically reduced. In order to completely eliminate the wetting phenomenon of the side wall, a vertical drainage zone is set.
locally between the retaining walls of the side wall of the side slope of the structure. The permeability coefficient \((\geq 3.4 \times 10^{-1}\text{cm} / \text{sec})\) is much larger than that of the concrete (about \(1.8 \times 10^{-11}\text{cm} / \text{sec}\)), guiding the groundwater flow line on the side slope of the slope to bring it to the hydrostatic pressure release layer of the base for discharging, so as to remove the possible influence of groundwater in the most economical way. The relevant analysis data and recommended design values are summarized in Table 5.

Table 5. Correlation analysis data and recommended design value of "Hydrostatic Pressure Relief technology" for structure.

| Mode Analysis results                  | Recommended minimum design value |
|----------------------------------------|----------------------------------|
| **Mining continuous rain 300mm / day critical rainfall analysis** |                    |
| Estimate the maximum base permeable volume (m\(^3\)/day) | 10.60                            |
| Estimate the maximum sidewall infiltration (m\(^3\)/day)   | 186.77                           |
| Estimate the maximum rainfall infiltration (m\(^3\)/day)   | 85.58                            |
| Base permeable system minimum laying area (m\(^2\))         | 96.32                            |
| Peripheral minimum laying area (m\(^2\))                    | 95.03                            |
| Peripheral minimum laying width(m)                           | 0.34                             |
| Base within the minimum laying area(m\(^2\))                 | Linear permeable tube arrangement (The base of the basement is not recommended for use) |
| The minimum laying width in the base(m)                      | -                                |
| Side wall vertical drainage minimum laying area(m\(^2\))     | 294.31                           |
| Side wall vertical drainage minimum width(m)                 | 0.15                             |
| Collection pipe minimum laying length(m)                     | 130.30                           |
| Outlet system diameter(mm)                                   | 40                               |
| Outlet system (Quantity)                                     | 2                                |

According to the groundwater seepage analysis, the maximum water level is designed to estimate that the After comprehensively considering the conditions of safety, economy, operation time and long-term use and maintenance convenience, the structure is fully laid on the substrate with a hydrostatic pressure releasing layer and is partially applied with a hydrostatic pressure releasing belt on the side slope of the upper slope to be satisfactorily completed Prevention of possible structural damage and long-term substrate, side wall leakage of water and other issues, and achieved good substantive benefits.

The system installation during construction started with excavation work. A flat surface provided proper work areas for the installation of the high-permeability choked flow filter, porous catchment pipe network, and superconducting seepage water grid mesh, as shown in Figures 8 to Figure13.
5.2 Comprehensive benefits and value

The practice of drainage anti-floating technology "Hydrostatic Pressure Relief technology" has the following benefits and values for the hillside structure: [15]

1) Avoidance of damage caused by lifting, structural damage or water infiltration at the centre of the foundation slab caused by continuous heavy rain during the construction of the basement shall be exempted from possible maintenance expenses.

2) Prevent unbalanced water pressure on the foundation and side wall of the structure, which may cause damage to the structure and damage of seepage water.
(3) Significantly reduce the cracks in the foundation slab, secondary construction joints and the lowest basement level’s wall waterproof plugging costs.

(4) Basement drier during construction to facilitate construction and quality control.

(5) To reduce the problem of property disputes caused by the leakage and dampness of the basement after prolonged use.

(6) To reduce the long-term loss of ventilation equipment required for the basement and electricity costs, as well as the basement to maintain the cost of the property.

(7) The finished basement has dry basement space, which will enhance the value of the building and the image of the developer.

(8) The foundation of the structure is converted into pressure-controlled by the mixed control conditions of pressure and buoyancy to reduce the differential settlement and enhance the disaster prevention benefit of the structure.

(9) Foundation water pressure reduction and maintain a balance, to protect the basement and sidewall reinforcement, concrete will not rust, deterioration, enhance the safety of hillside structures and disaster prevention benefits.

6. Conclusions
Based on the analysis of this article and examples, the anti-disaster benefit and value of drainage anti-floating technology "Hydrostatic Pressure Relief technology" applied to hillside structures are as follows:

(1) In addition to factors such as geological conditions and water and soil conservation, the impact on ground structures of various types of groundwater and surface water must be considered in a comprehensive and prudent manner in planning so as to enhance disaster prevention design safety to prevent long-term use of the structure suffered structural damage or inconvenience caused by the situation.

(2) Hillside structures may be affected by unbalanced groundwater pressure:
   A. Basal floor due to buoyancy caused by the destruction or floating phenomenon.
   B. Basement wall due to water pressure caused by water seepage, humidity or deformation and so on.

   The design time should take into account the highest groundwater level during continuous heavy rains and the long-term safety, to comfort and maintain the structure

(3) The laying of hydrostatic pressure release layer on hillside structure can effectively eliminate the harm of groundwater and enhance the long-term disaster prevention benefit. Under the conditions of suitable geological conditions and structural properties, it can be used as an economical and effective anti-seepage and prevention and control of slope structural degradation of solutions.

Sources of groundwater from hillside structures are mainly concentrated on the periphery and side walls of the basement. The possibility of groundwater release can be fully relieved by the laying of a hydrostatic pressure release layer on the basement and the provision of vertical drainage belts between the retaining walls of the side slope of the upper slope. To develop the substrate water pressure effective control and uniformity of the results, optimize the structure to the best economic benefit outcomes.

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