Realistic Estimation of Water Table Depth for Design Optimisation of Bored Tunnel and Cut and Cover Structures for Underground Metro

Chiranjib Sarkar, Sibapriya Mukherjee, and NKumar Pitchumani

Abstract With the rapid expansion of urban transportation systems, tunnels and cut & cover structures are considered as the only solution in improving the urban space congestion problem in mass rapid transit system. Therefore, it is necessary to accurately design underground structures with realistic assumptions and considerations of design parameters like site geotechnical data, water table, surcharge load, etc. Over-conservative approach provides not only uneconomical design but also frequently results in overdesign of the structures. Water table depth has a significant role in some design aspects of underground structures like floatation check, lateral and uplift pressure on the buried structure, etc. In the current practice of tunnel and cut & cover structure design, water table is assumed to coincide with the ground level. Most of the Design Basis Reports & Outline Design Specifications directly mention consideration of water table at ground level for floatation check and load calculations, etc. However, the actual scenario is different in most of the cities, especially in northern, central, western and eastern regions of India except the coastal cities. In the present study, an attempt has been made to carry out a parametric study on the effect of water table depth in the design of a typical 6.3 m outer diameter circular tunnel with a 6 m backfill. In this study, it is also attempted to establish an analytical method of calculating the most realistic consideration of water table depth instead of the present hypothetical assumption of considering water table to coincide with the ground level. The findings of the current study may be helpful to the researchers and practising engineers in the design of tunnel and cut & cover structure for subways and metros.

Keywords Underground structure · Water table · Floatation

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1 Introduction

Underground infrastructure is being extensively used to tackle urban space congestion arising from land insufficiency. Metro railway is considered as a lifeline for development of any city. A metro rail project should be planned and designed in such way that it can provide a socially, economically and environmentally sustainable transport network. Hence, the design of tunnels and underground structures should be done with realistic assumption and actual site-specific consideration of design parameters like site geotechnical data, water table, surcharge load, etc. It is a well-known fact that over-conservative approaches provide uneconomical and unrealistic situations. Water table depth has an important role in some design aspects of tunnel and underground structure like liquefaction analysis, floatation check, applicability of lateral and uplift pressure on the buried structure, etc. In the existing practice of design of a tunnel and cut & cover structure, water table is assumed to coincide with the ground level, whereas actual level of water table is totally different in most of the cases. Like soil profile, water table varies from location to location and project to project. Each project and location has its own uniqueness in water table depth which depends on many factors and parameters. Therefore, water table or hydrostatic pressure consideration in design should be project specific. The existing common and typical concept of considering water table at ground level is hypothetical, over-conservative and misleading. There is high time now to rethink or to start comprehending realistic consideration of water table in design of tunnel and underground structures. The present paper suggests that water table depth should be considered as project-specific instead of generalising for all projects. Water table depth has a significant impact on the following design aspects of tunnel and underground structures:

(a) Lateral and uplift pressure,
(b) Floatation,
(c) Overburden pressure and ground deformation and
(d) Liquefaction analysis.

A. Lateral and uplift pressure

Hydrostatic loads (lateral pressure and vertical uplift) applied on tunnel and underground structure are directly proportional to the depth of water table. Intensity of hydrostatic load/water pressure (lateral and uplift) varies based on water table depth below the ground. It increases when the water table depth below ground reduces, whereas it decreases when the depth of water table increases. Hence, the selection of proper water table depth from the ground is an important part of the design of tunnel and underground structures. A schematic view of application of lateral water pressure and vertical uplift pressure on cut & cover box tunnel structure is shown in Fig. 1. Lateral water pressure acting on cut & cover box tunnel wall for different water table depths (water table at ground, water table at 2 m below ground and water table at 4 m below ground with the RL of the ground level being 118.5 m) are shown in Fig. 2

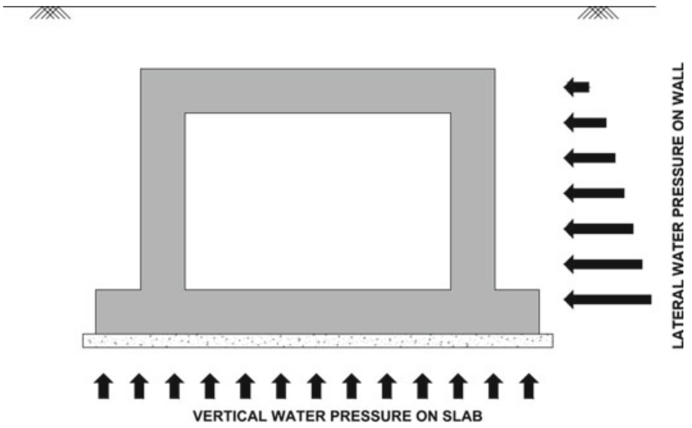

Fig. 1 Schematic view of lateral water pressure and vertical uplift pressure acting on cut & cover box tunnel structure

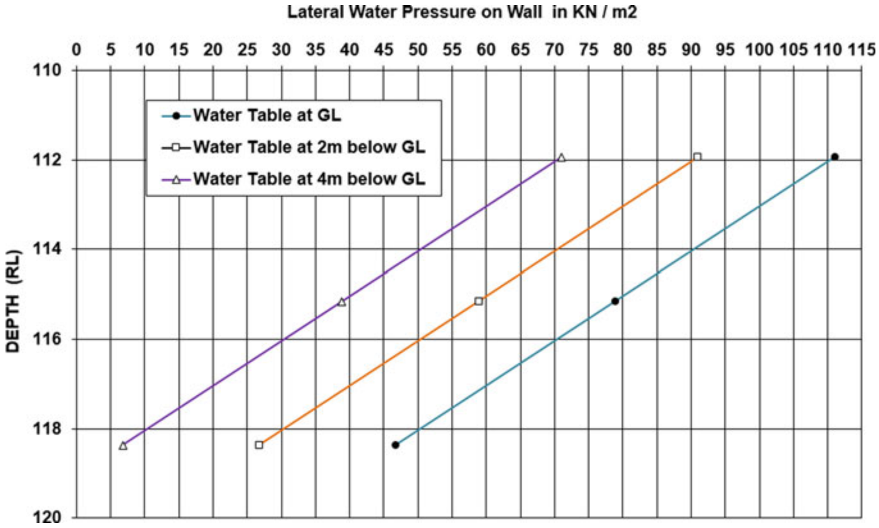

Fig. 2 Comparison of lateral water pressure acting on cut & cover box tunnel wall for different water table depths (water table at ground, water table at 2 m below ground and water table at 4m below ground)

B. Floatation

The present trend for flotation check is to assume water table coincidence with ground level (Report of the Ground Water Resource Estimation Committee (GEC-2015) 2017). This seems to be hypothetical. In most of the cases, the actual water table is totally different from the present consideration and it varies from location to location and project to project. As per the current concept for floatation check, the design assumes that the entire structure is submerged under water and a buoyant force is acting as uplift force on the bottom of the structures, but the actual scenario is much different in the case of a deeper water table. It is a fact that the water table never coincides with ground level (in the case of higher water table) even in flood or any adverse situation. Hence, it is necessary to adopt an appropriate depth of water table for flotation check.

C. Overburden pressure and ground deformation

Overburden pressure and ground deformation have a direct relationship with water table depth. With the variation of water table depth, overburden pressure and ground deformation also fluctuate. Hence, selection of proper water table depth from the ground is required for the calculating of actual overburden pressure and ground deformation.

D. Liquefaction analysis

Liquefaction Potential is directly related with effective vertical stress which is also dependent on water table depth. As per the current practice of liquefaction analysis, it is assumed that the water table is coincident with ground level. This is not the correct approach. Water table should be location and project specific instead of taking it at ground level. Hence, it is essential to adopt a suitable depth of water table for liquefaction analysis

In the ongoing practice of design of tunnel and cut & cover structures, water table is assumed to coincide with the ground level. Most of the Design Basis Reports (DBR) & Outline Design Specification (ODS) for metro projects have directly stated to consider water table at ground level for liquefaction depth calculation and floatation check (Model design basis report (DBR) for bored tunnel sections of metro system in India. Ministry of Railways (Railway Board), Government of India, March 2017; Corporation 2019). Furthermore, design load and load conditions can be referred from the guideline mentioned in ‘Model design basis report (DBR) for bored tunnel sections of metro system in India’. As per guideline, design loads and load cases would be calculated by considering water table at ground surface (Model design basis report (DBR) for bored tunnel sections of metro system in India. Ministry of Railways (Railway Board), Government of India 2017). But water table at tunnel stretch varies from location to location and project to project. Therefore, the actual scenario of most of the cities in India (except the coastal cities) are different from what is mentioned in the guideline for design of tunnel and underground structure. In the present paper, an attempt has been made to find out the effect of water table depth in design of a typical cut & cover box tunnel and a circular tunnel with 6m backfill. The present study also encompasses an analytical method for calculating the most realistic consideration of water table depth instead of the present hypothetical assumption of water table at the ground level.

2 Model of the study

2.1 *Project-Specific Hydrological Feature Study*

Two projects from two different cities have been considered for this study and analysis. The first one is a typical circular tunnel (6.3 m outer diameter) section of the Delhi Metro Dwarka–Najafgarh corridor. Actual groundwater table has been observed between 18.0 and 19.0 m below ground level during soil investigation. A seasonal fluctuation in water table, of an average of 2 m, has been found for Delhi region (Ground Water Year Book NCT Delhi xxxx). Depth of water table and groundwater contours of the National Capital Territory, Delhi (CGWB, 1995), are shown in Fig. 3.

There are two main aquifers within the route; the alluvium and the rock. Groundwater flow within the alluvium is controlled by inter-granular flow and it is a variable depending upon the spatial form of the historical channel deposits, while flow within the rock is controlled by fissures. Recharge of the aquifers occurs from the Yamuna River catchment via the alluvium, and from the Aravalli Range via the basement rock. The highest flood level (HFL) at the Yamuna River is recorded at 209.86 m, whereas the lowest bed level (LBL) or lowest water level (LWL) is 206 m. Hence, the depth of water at the highest flood level is near about 4 m (3.86 m).

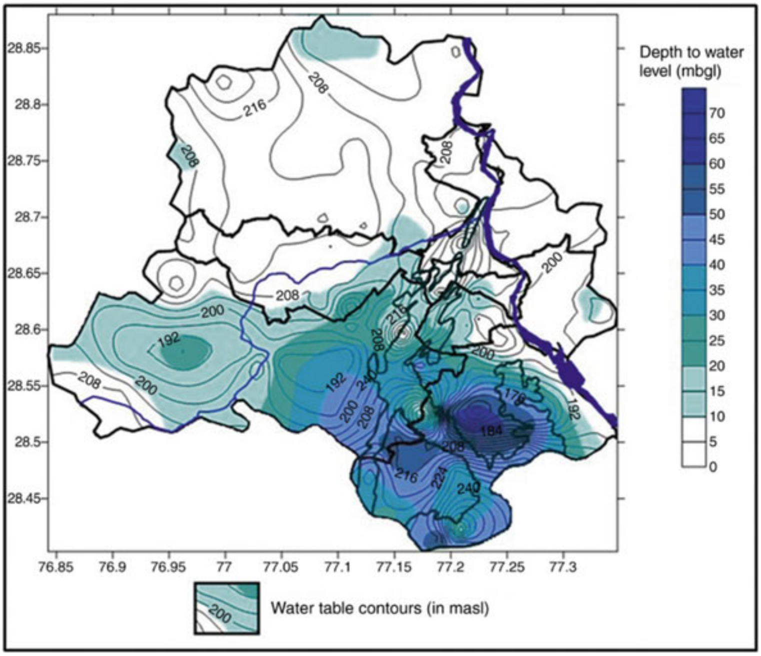

Fig. 3 Depth of water table and ground water contours of National Capital Territory, Delhi

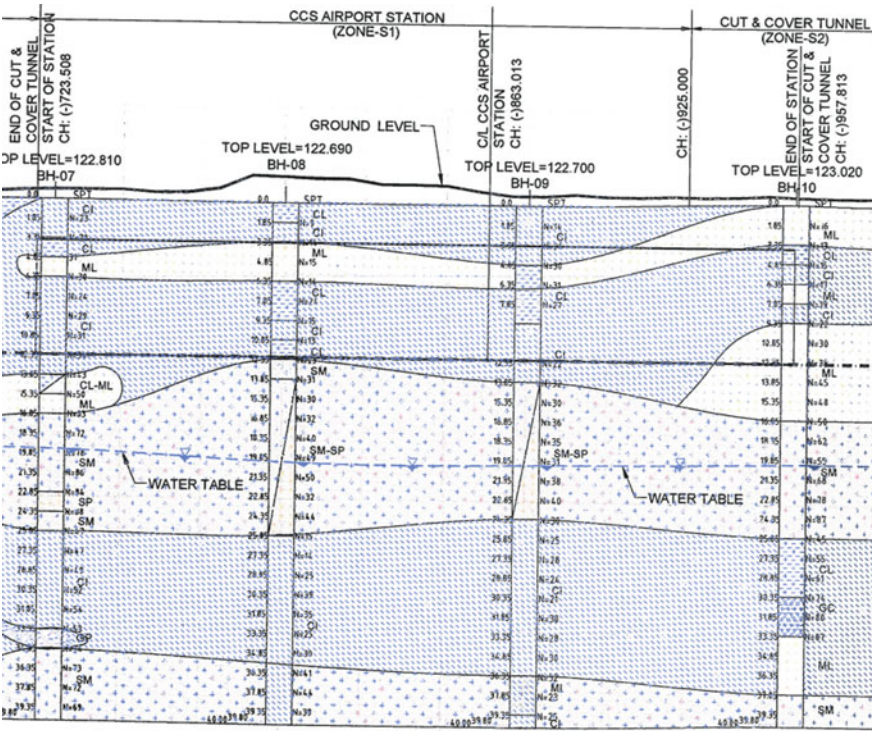

Fig. 4 Long section of geotechnical profile with water table of 18m near CCS Airport station

The second project is a typical cut & cover tunnel (9.6 m wide x 5.8 m high) stretch in the north–south underground corridor of Lucknow metro. Actual groundwater table has been observed near about 18.0m below ground level during soil investigation. Long section of geotechnical profile with water table of 18.0m near CCS Airport station area is shown in Fig. 4.

More than 80% of the land area in Lucknow City is situated on the Central Ganga alluvial plain and stretches on both sides of the Gomti River. The highest flood level (HFL) at the Gomti River is recorded at 111.60 m (in 1960), whereas the lowest bed level (LBL) or the lowest water level (LWL) is 107.4 m (Hydrological Study for Gomti River Front Development 2013). Hence, the depth of water at the highest flood level is near about 4.2 m. Groundwater level zones of Lucknow city area (Ground Water Department, Uttar Pradesh, 1995) are shown in Fig. 5.

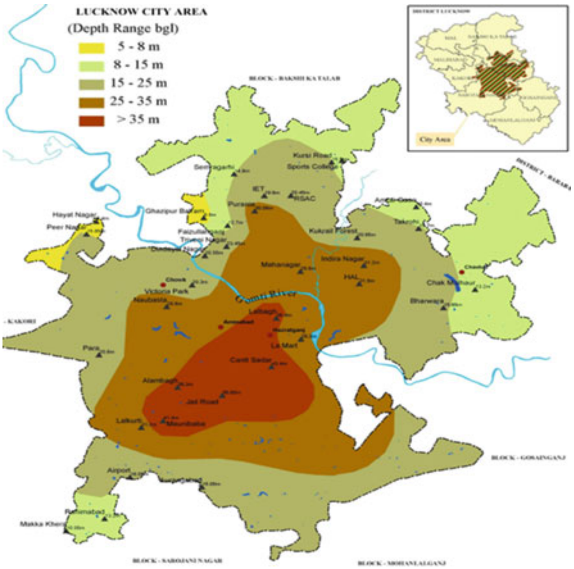

Fig. 5 Ground water level zones of Lucknow city area

2.2 *Parametric Study on the Effect of Water Table*

An attempt has been made to carry out a parametric study on the effects of water table depth in design of a typical 6.3 m outer diameter circular tunnel with a 6 m backfill. A two-dimensional numerical analysis (using finite element method) with 0.5 X 0.5 m mesh size has been developed with geotechnical software MIDAS GTX NX with consideration of water table at tunnel top level and tunnel centre level.

3 Groundwater Estimation Model Study

The assessment of groundwater comprises of dynamic groundwater resources and in-storage groundwater resources.

3.1 *Assessment of Dynamic Groundwater Resources*

Ground Water Estimation Committee-2015 proposed a methodology for the estimation of dynamic ground water resources based on the principle of water balance, i.e. Inflow – Outflow = Change in Storage (of an aquifer). This principle can be further elaborated by Eq. (1) as follows:

$$\Delta S = R_{RF} + R_{STR} + R_{C} + R_{SWI} + R_{GWI} + R_{TP} + R_{WCS} \pm VF \pm LF - GE - T - E - B \quad (1)$$

where,

ΔS—Change is storage of an aquifer
R_{RF}—Recharge from rainfall
R_{STR}—Recharge from stream channels
R_c—Recharge from canals
R_{SWI}—Recharge from surface water irrigation
R_{GWI}—Recharge from groundwater irrigation
R_{TP}—Recharge from Tanks and Ponds
R_{WCS}—Recharge from water conservation structures
VF—Vertical inter-aquifer flow
LF—Lateral flow along the aquifer system
GE—Groundwater Extraction
T—Transpiration
E—Evaporation
B—Base flow

It is a fact that detailed groundwater budgeting of some assessment units is not possible due to the absence of a proper database. Hence, the estimation is carried out by using lumped parameter estimation approach.

3.2 Assessment of In-Storage Groundwater Resources

Assessment of in-storage groundwater resources or static groundwater resources can be made after defining the aquifer thickness and specific yield of the aquifer material. Ground Water Estimation Committee-2015 proposed a methodology for the estimation of in-storage groundwater resources which can be further elaborated by Eq. (2) as follows:

$$SGWR = A \text{ x } (Z_2 - Z_1) \text{ x } S_Y \tag{2}$$

SGWR = Static or in-storage Groundwater Resources
A = Area of the Assessment Unit
Z_2 = Bottom of Unconfined Aquifer
Z_1 = Pre-monsoon water level
S_Y = Specific Yield in the in-storage Zone

The sum of annual usable groundwater resources and the in-storage groundwater resources is the total groundwater availability of an aquifer.

4 Results and Discussions

The outcomes of the present study are as follows:

4.1 Effects of Different Water Table Depths on Design of Tunnel at the Same Depths with Same Ground Condition

To address the effect of different water table depths on design of tunnel at the same depth with same ground condition, a 2D finite element analysis has been performed on a typical 6.3m outer diameter circular tunnel with 6m backfill with considerations of water table at tunnel top level and tunnel centre level. Bending moment of typical 6.3m diameter circular tunnel at same depth with same ground condition and water table at tunnel top level is shown in Fig. 6 and with the water table at tunnel centre level is shown in Fig. 7.

From the results of the above-shown figures, it is clear that the bending moment decreases with the increase of depth to water table below ground, even when tunnel depth and ground condition remain the same. As the behaviour of structure changes with the changes of water table depth, therefore, water table should be used as

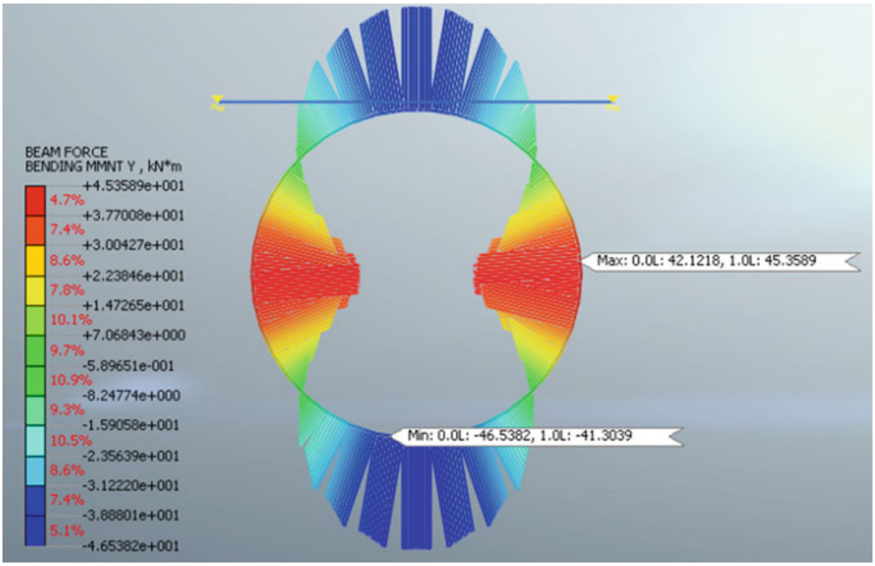

Fig. 6 Bending moment of typical 6.3 m diameter circular tunnel at same depth with same ground condition and water table at tunnel top level

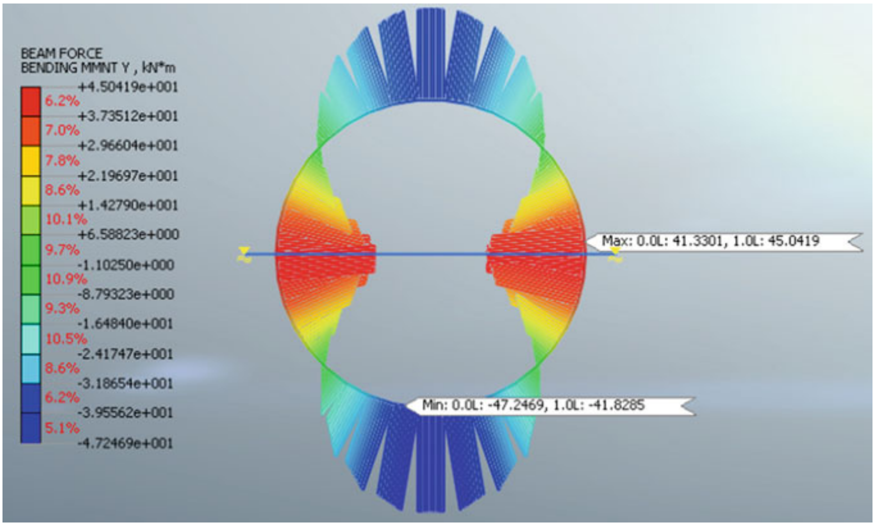

Fig. 7 Bending moment of typical 6.3 m diameter circular tunnel at same depth with same ground condition and water table at tunnel centre level

location- or project-specific instead of the present practice of considering water table at ground.

5 Review of Project-Specific Hydrological Model and Proposed Methodology of Groundwater Estimation

From project-specific actual hydrological data, it can be observed that actual water table is at much deeper levels than hypothetical consideration of water table at ground level as the present concept.

Due to seasonal fluctuation (pre-monsoon and post-monsoon cases), an average of 2m depth would be additionally required to include with actual groundwater table measured during soil investigation at project site. Generally, design life of urban transportation structures is mostly in the range of 100–120 years. Therefore, the possibility of the highest floods and their depth may also be assessed statistically. The depth of water at the highest flood level (HFL−LBL/LWL) would be included with groundwater table.

Based on the principle of water balance, i.e. Inflow − Outflow = Change in Storage, and review of groundwater estimation model, a reasonable water table for tunnel design can be proposed as the sum of actual groundwater table measured during soil investigation at project site, 2m depth for seasonal fluctuation and depth of water at the highest flood level (HFL−LBL/LWL). This principle can be further elaborated by Eq. (3) as follows:

$$\text{Water table depth for tunnel design} = \text{Actual ground water table}$$
$$\text{(measured during soil investigation at project site)} + 2\text{m (for seasonal fluctuation)}$$
$$+\text{Depth of water at highest flood level} \quad (3)$$

In the case of liquefiable soil, maximum value between the liquefaction depth and the highest flood level depth would be used in place of the highest flood level depth.

Equation (3) can be further illustrated with a working example for a location, where the actual groundwater table is observed at RL (+) 80m (20m below the ground level) and the depth of water at the highest flood level is found as 4m. Thus, water table depth for design will be calculated as (80+2+4) = 86m, i.e. (20−2−4) = 14 m below the ground level.

6 Conclusions

The present study tried to establish an analytical method for proposing a realistic depth of water table instead of the present hypothetical assumption of considering water table at ground level. The conclusions drawn from the current study and analysis are as follows:

(i) Water table should be considered as location- or project-specific instead of the present practice of considering at ground.
(ii) Project-specific water table depth (refer to Eq. 3) is defined as a sum of actual groundwater table at project site, 2 m depth for seasonal fluctuation and depth of water at the highest flood level. This proposed project-specific reasonable water table will have a significant impact in the optimisation of tunnel design in most of the cities, especially in northern, central, western and eastern regions of India except the coastal cities.
(iii) Liquefaction analysis and floatation check should be done with project-specific water table depth (refer to Eq. 3).
(iv) During design load and load conditions calculation, lateral water pressure, vertical uplift pressure, overburden pressure, etc., should be calculated with project-specific water table depth (refer to Eq. 3).
(v) For design of any temporary structure or any temporary and construction stage analysis, actual groundwater table at project site with an additional 2m depth for seasonal fluctuation should be used.
(vi) Moreover, an intensive investigation of project/location-specific hydrological data and upgradation of the current conventional concept is further required in design of structures other than underground like entry, exit, ancillary building, above-ground structure, etc.

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