Geotechnics of Artesian Flow – Case Study of River Shivganga, Nepal

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Abstract: Geotechnical investigations done for the bridge across River Shivganga on the Kohalpur-Mahakali Highway in the Terai region of southwestern Nepal reveal the occurrence of multiple layers at different depths with artesian ground water flow. The concept for foundation design in such strata should consider three aspects – (a) bed boiling (quick condition) should not develop even if maximum scour occurs, (b) during construction, a minimum soil cushion thickness should be available between foundation level and strata with artesian flow, and (c) for long term stability, the bearing capacity at artesian level should be computed using effective stress principle. The application of these concepts to fix the founding levels for well foundations for the bridge is discussed.

1 INTRODUCTION

Artesian flow is likely to occur where a confined granular deposit with hydraulic gradient is sandwiched between two cohesive strata. Geotechnical investigations as well as foundation design and construction in strata with artesian flow present a challenge to the geotechnical engineer, structural designer and construction engineer alike. This paper presents the authors' experience in conducting geotechnical investigations in such strata.

A case study of geotechnical investigation for bridge across River Shivganga in southwestern Nepal is presented in this paper. At this bridge location, artesian conditions were met in three confined granular strata at different depths.

Review of literature indicated practically no design approaches to tackle this problem. Concepts for foundation design developed by the authors include (a) check against *"bed boiling"*, (b) ensuring a minimum *"soil cushion thickness"* between foundation and stratum with artesian pressure and (c) determining soil bearing capacity using *"effective overburden pressure"*.

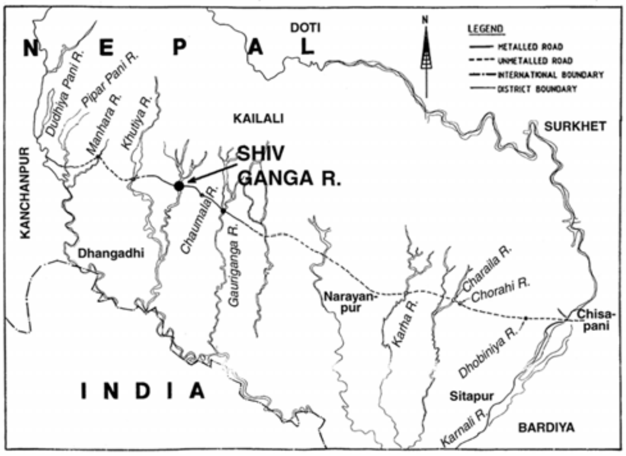


Fig.1. Vicinity Map

2 PROJECT DETAILS

The bridge across River Shivganga is in southwest Nepal. It is on the Kohalpur-Mahakali Highway, which runs almost parallel to the Indo-Nepal border, about 15-30 km inside Nepalese territory. Fig.1 presents a vicinity map showing the highway alignment and important rivers of the area.

2.1 *Regional Geology*

The region between the Rivers Mahakali, Seti and Karnali expose the Siwaliks and the Lesser Himalayas to the north of the Main Boundary Thrust (Bashyal, 1982). The area is bordered by Kumaon Himalayas in the north and west and Indo-Gangetic alluvial plains in the south.

The Siwalik foothills occupy a wide belt and reach a width of 52 km in southwestern Nepal. The Nepalese sub-Himalayas belt has been classified into the Lower, Middle and Upper Siwaliks (Gansser, 1964). Most of the visible sediments belong to the Middle Siwaliks and are of Middle to Late Miocene & Pliocene to Pleistocene Age (West & Munthe, 1981).

The Recent deposit of alluvial fan comprises pebbles and boulders set in a sandy/silty matrix. The foothills along the Indo-Nepal border are called the Terai region and are very fertile and well drained. Terrace alluvium is restricted to the paleobanks of the rivers. It is made up of coarse clusters (pebbles and boulders with sand) in the upstream reaches and grades into finer sediments downstream.

2.2 *River Details*

Shivganga is a seasonal river. It is in the foothills zone of the Himalayas, called the Terai plains. It is prone to flash floods, during which there is substantial erosion and deposition.

There is substantial flow of underground water due to the hydraulic gradient between the catchment area in the upstream hills and the Terai plains. Therefore, artesian conditions are encountered at many locations in this area. It is equivalent to a flowing underground river and is to be treated as a hydrodynamic aquifer.

2.3 *Site Stratigraphy and Measured Artesian Heads*

Cross sectional profiles at the bridge location showing the distribution of the strata along the bridge alignment is presented on

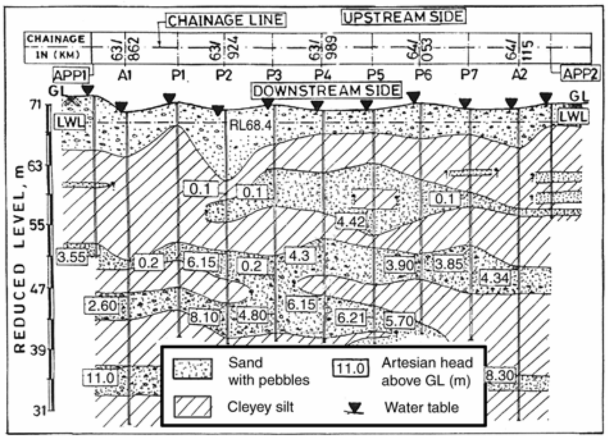


Fig.2 (Cengrs. 1996). The artesian head, measured as height of

Fig.2. Site Stratigraphy: Bridge over River Shivganga

the water column above the ground level at the borehole location at the time of the investigation is also shown on Fig.2.

Figure 3 shows the artesian water overflowing from the casing during geotechnical investigation.

It may be seen from Fig.2 that three confined granular strata with artesian pressure is encountered as listed below:

(i) The first confined sand stratum is met below 7 to 12 m depth in which the artesian head recorded ranges from a minor flow to 4.4 m above ground level.
(ii) The second confined stratum of sand with gravel and pebbles is met below 17-20 m depth. The head recorded ranges between 3.85 to 8.1 m above ground level.
(iii) The third stratum with artesian head was met below 33 to 34.5 m depth. The artesian head recorded in this stratum is as high as 8.3 to 11.3 m above ground level.

3 DISCUSSIONS

The data presented herein is based on the geotechnical investigations conducted during the period 1996-97 in a stretch of about 70 km of the Kohalpur-Mahakali Highway in southwestern Nepal. Nine major bridge locations were investigated along this stretch for this project and artesian conditions were encountered. As per available information, artesian conditions are encountered at several locations along the Kohalpur-Mahakali Highway in southwestern Nepal.

Higher artesian heads were measured during monsoon season (July-August). The artesian pressures measured during October are relatively less. It is likely that during the peak summer season, the artesian pressure may be small and not noticeable. This suggests that the period during which the investigation is conducted should be carefully planned. Investigations conducted during the lean flow season could miss out on a likely artesian condition thus leading to a wrong assessment of site conditions and an unsafe foundation design.

Continuous observation should be made of the level of water in the borehole, particularly when the drilling meets a confined sand layer. Where there is a artesian flow, the static water level in the borehole will rise. Water will overflow from the borehole if the artesian head exceeds the depth of the artesian layer below ground level.

Fig 3. Artesian Water Gushing out of Casing

At some borehole locations, nominal or nil artesian head was encountered in some confined granular strata during the period of the investigation. However, artesian head was noticed in adjoining boreholes in the same stratum. For the purpose of design, the highest head recorded in each stratum should be considered as the head that could develop and further modified suitably to reflect the worst conditions.

The recorded artesian head varies from day to day. It appears to be a function of the flood condition in the river and rains in the upper reaches of the hills. The discharge and artesian pressures depend upon the intensity of rains in the catchment areas of the upstream hilly region, extent of underground water flow and recharging of the aquifer.

It was noticed that when the river is in spate, the artesian head increases substantially suggesting that the flood not only causes increased surficial flow but also increases the underground water flow. During fair weather conditions in the catchment area, when flow of water in the river is nominal, the artesian heads recorded are relatively less, and at times nil artesian head is observed. It is apparent that the maximum artesian pressure recorded should be suitably increased to reflect the worst condition.

At a nearby bridge location, localized “bed boiling” was observed. Water was seen bubbling out of the ground at such points creating a depression / subsidence of soil. This happens because the overburden above the strata with artesian flow is unable to sustain the artesian pressure. It was also noticed that the point at which bed boiling occurs (the artesian point) tends to shift with time with change in underground flow regime and scour of the surficial strata, exhibiting hydrodynamic aquifer characteristics. Figure 4 shows quick condition developed during geotechnical investigations due to artesian puncturing through overlying strata.

It is therefore essential that a careful assessment of the artesian condition be done so as to make a reasonable assessment of maximum artesian pressure that could occur during the life span of the structure. The current study has made no attempt to make a long-term assessment.

4 PROPOSED FOUNDATION DESIGN CONCEPT

The eight span bridge has seven piers and two abutments. The to-

Fig.4. Quick Condition Developed during Geotechnical Investigation.

tal length of the bridge is 257.5 m and the spans are 32.2 m long. The average bed level is at about RL 70.3m. The low water level (LWL) is at RL 68.4 m and the maximum scour level is RL 66.4 m at the abutments and RL 63.6 m at the pier locations.

The downward load at the pier top is estimated to be about 8500 kN. For such bridges with high loads and substantial scour (6.7 m at pier location), it is normal practice to provide well foundations. For this bridge, it was planned to provide 6 m diameter wells for the piers and 8 m diameter wells for the abutments.

The following foundation design concepts were developed by the authors as a first attempt to work out a geotechnical solution for this problem.

4.1 *Foundation Depth*

On account of multiple artesian layers, the depth of foundation will depend upon the depth of each layer. In case the first artesian layer is fairly deep, shallow well foundation with well tip in clayey strata, which is sufficiently above the strata with artesian pressure, is a suitable foundation scheme.

In case of artesian layer being at shallow depth, the well foundation may be required to go deeper, crossing one or two artesian layers. The well tip may be founded below the artesian layer, preferably in clay layer, which is sufficiently above the underlying artesian layer.

A deep well with well tip in sand layer may be required at some cases depending upon the stratigraphy. Construction / sinking of the well should be done during the fair weather season during which the artesian pressures are relatively small. In this case, adequate precautions should be taken to ensure that the bridge remains stable even during the worst situation.

4.2 *Design Criteria*

In addition to the usual checks for bearing capacity safety factor and settlement of the well foundation under the anticipated load, foundation design in strata with artesian flow is governed by the following technical considerations:

(i) The stability of riverbed is to be ensured against boiling due to artesian pressures (quick condition) from various layers if scouring upto maximum scour level takes place.

(ii) It should be ensured that sufficient soil cushion is available between foundation tip level and the artesian level, so that the artesian pressure does not puncture through soils below founding level during construction period. If it is not possible to provide sufficient thickness of the soil cushion, necessary precaution should be taken during the construction stage by providing positive head of water by providing false steining to counter-balance the artesian pressure.

(iii) The effective soil bearing capacity available at the artesian level should be more than the pressure induced by the foundation at that level with an adequate safety factor.

4.3 *Stability of River Bed (Bed Boiling)*

The stability of bed against quick condition under maximum scour condition is to be checked for the foundation system. In case, due to artesian conditions, bed boiling (quick condition) is likely to take place, necessary bed protection will be required to minimize scouring and to avoid instability due to boiling of bed.

If effective overburden pressure at artesian level during the time the maximum scour has occurred becomes negative (less than 0), *"bed boiling"* (quick condition) will occur. The artesian will puncture through the overburden resulting in instability of the riverbed.

Effective overburden pressure at artesian Level

$$= q' = \Upsilon_t\, a - u$$

where

Υ_t = bulk density of soil
a = thickness of soil strata between max. scour level and artesian level
= RL of scour level – RL of artesian level
u = Pore water pressure
= Maximum expected artesian pressure in artesian layer.
= Υ_w [(RL of GL – RL of strata with artesian head) + p]
Υ_w = unit weight of water
p = artesian head above ground level

To protect the bed from boiling ($q' \le 0$), adequate bed protection should be done so as to avoid instability. The bed protection should be done upstream and downstream of the structure up to sufficient length so that the shifting nature of the artesian point, which could trigger *bed boiling* does not endanger the stability of the structure.

4.4 *Soil Cushion Thickness*

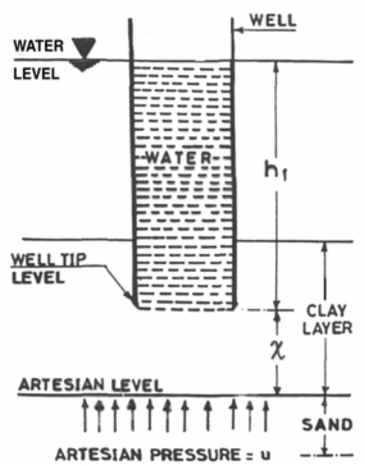
At the well tip level, it is essential that the soil cushion between the well tip and the artesian (sand) layer is sufficient to resist the uplift pressure due to the artesian condition. This condition is most critical during the construction period. While the well is being sunk, the water level inside the well should be maintained above ground level or water level in the river, whichever is higher. If boiling is observed while sinking, water level inside the well should be increased to create a positive head so as to counter balance the artesian head by provision of false steining. Figure 5 is a schematic explaining this concept.

Downward Pressure = Water head inside well + pressure due to soil cushion
$= h_1\, \Upsilon_w + \chi\, \Upsilon_t$

Uplift Pressure, u = Maximum expected artesian pressure at layer below well tip
$= (h_1 + \chi + p)\Upsilon_w$

For stability purpose,

$$h_1\, \Upsilon_w + \chi\, \Upsilon_t \ge (h_1 + \chi + p)\Upsilon_w$$



h_1 = depth of well tip below ground level; Υ_w = unit weight of water;
χ = thickness of soil cushion between well tip and underlying sand (artesian level) layer; p = highest expected artesian head above G.L.;
$\Upsilon' = \Upsilon_t - \Upsilon_w$ = submerged density of soil

Fig.5. Soil Cushion Thickness Above Artesian Level

Hence, $\chi \geq p\Upsilon_w / \Upsilon'$

Minimum Thickness of Soil cushion should be equal to $p\Upsilon w/\Upsilon'$ for factor of safety equal to 1.0.

4.5 *Effective Soil Bearing Capacity at Artesian Level*

The effective soil bearing capacity available at the artesian level should be more than the pressure induced by the foundation at that level with an adequate safety factor. Figure 6 explains this concept.

Gross Applied Soil Pressure at well tip = q_G
Net Applied Soil Pressure at well tip = $q_n = q_G - \Upsilon' h_1$
Effective overburden pressure at artesian level = $q' = \Upsilon_t (h_1 + \chi) - u$
Uplift Pressure, u = $(h_1 + \chi + p)\Upsilon_w$
Effective safe bearing capacity of artesian layer (soil resistance) = q_{ga} = $[q' N_q \zeta_q d_q + 0.5 B \Upsilon' N_\gamma \zeta_\gamma d_\gamma]$
Total stress at Artesian level = Superimposed stress + effective overburden pressure = $I_z q_n + \Upsilon' (h_1 + \chi)$

where I_z is the influence factor for the loaded area at depth χ below well tip using appropriate stress distribution theory. N_q & N_γ are bearing capacity factors; ζ_q & ζ_γ are shape factors; d_q & d_γ are depth factors.

If effective soil resistance at artesian level (q_{ga}) is less than the effective stress from superimposed loading, the artesian layer will yield under superimposed loading.

4.5 *Fixing of Foundation Levels*

Due to multiple layers with artesian flow, shallow wells were preferred over deep wells. Analysis for bed boiling condition indicated that for maximum scour, the artesian may puncture through the overlying strata. For the stability of the shallow wells, it was decided to provide bed protection in the vicinity of the bridge on both upstream and downstream side.

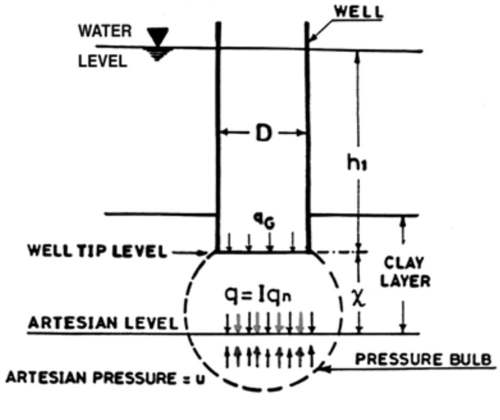


Fig.6. Distribution of Stresses Below Well Tip

Once bed protection is provided, scour will not occur. Most wells were about 7m below LWL (RL 61.4 m). The wells were kept above the artesian layer, ensuring adequate soil cushion thickness. At few pier locations, sand layer was encountered at the proposed well founding level. At such locations, the well tip was taken deeper, beyond the top sand layer, which is liable to experience artesian pressure during the life of the bridge. The well tip was founded on an underlying clayey silt stratum. During construction, false steining was provided above GL, where required as per site conditions, so that the artesian water does not cause sand boiling.

5 CONCLUDING REMARKS

This paper is an attempt to report the unusual but problematic phenomenon of foundations under artesian condition. Further research is required to make a detailed study of this problem. Long-term field observations are needed to understand the enormity of the hydrodynamic artesian flow and the performance of foundations under such ground conditions. A field study based methodology to assess the maximum artesian pressure that could occur should be developed to approach this challenging problem in a scientific manner.

ACKNOWLEDGEMENTS

The authors are grateful to M/s. Gammon India Ltd. for giving opportunity to Cengrs Geotechnica Pvt. Ltd. to carry out this investigation; Ministry of Surface Transport (Govt. of India) and M/s. RITES (Bridge Division) for their encouragement.

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