

DEEP FOUNDATIONS UNDER ARTESIAN CONDITIONS

SANJAY GUPTA

Managing Director

RAVI SUNDARAM

Director

Cengrs Geotechnical Private Limited, New Delhi

SYNOPSIS - Geotechnical investigations done at sites of bridges along the route of the Kohalpur - Mahakali Highway in the Terai region of Western Nepal revealed the occurrence of artesian groundwater flow in granular strata confined between clay layers. The paper discusses the methodology adopted for the geotechnical investigations. The concept for foundation design in such strata should consider three aspects - (a) *bed boiling* (quick condition) should not develop even after scouring, (b) during construction, minimum *soil cushion thickness* should be available above the artesian layer so that the artesian pressure does not puncture through, and (c) for long term stability, the bearing capacity at artesian level should be calculated using the *effective overburden pressure*.

INTRODUCTION

Artesian flow is likely to occur where a confined granular deposit occurs sandwiched between two cohesive strata. Geotechnical investigations as well as foundation design and construction in strata with artesian flow presents 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 review of literature revealed practically no field data on artesian conditions. This paper is a first attempt to share the field observations and experiences on the subject. This problem further gets complicated due to varying and shifting nature of artesian phenomenon and also multiple artesian layers with artesian flow.

Concepts for foundation design presented here 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*"

PROJECT DESCRIPTION

The Kohalpur - Mahakali Highway runs almost parallel to the Indo-Nepal border, about 15 to 30 km inside Nepalese territory. The sector investigated is in south-west Nepal in District Kailali. Several bridges are being constructed across minor and major rivers along the road alignment. Fig.1 presents a vicinity map showing the route investigated and important rivers of the area.

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 borders with the Kumaon Himalayas in the north and west and the Indo-Gangetic alluvial plains in the south.

The Siwalik foothills occupy a wide belt and reach a width of 52 km in south-western 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).

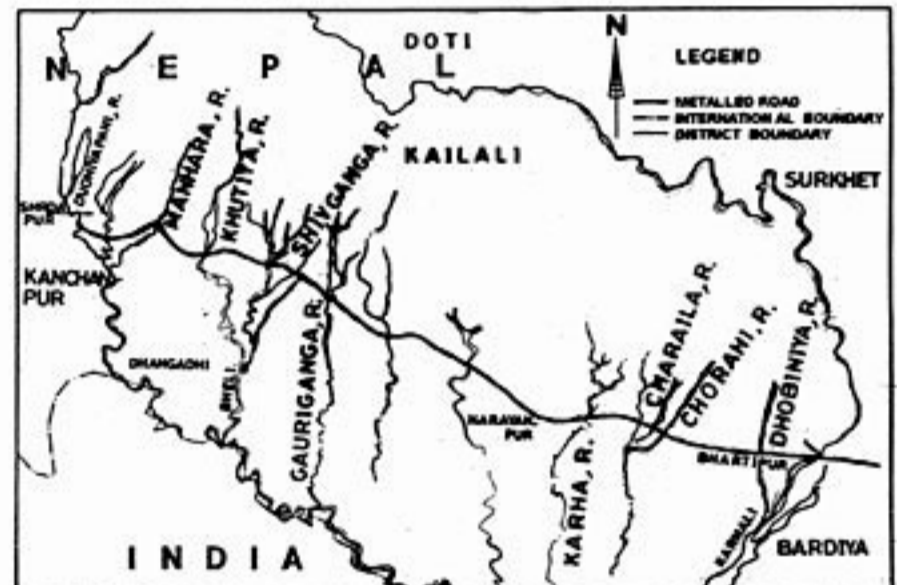


Fig.1 : Vicinity Map

The Recent deposit of alluvial fan comprises pebbles and boulders set in a sandy/silty matrix. The foothills along the Indo-Nepal border is called the Terai region and is 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.

RIVERS OF AREA

The rivers of south - western Nepal are mostly seasonal. Karnali is the most important river of the area and all the rivers in this district flow into Karnali.

The rivers meander over the Terai plains, shifting course somewhat over the years, with erosion and deposition during

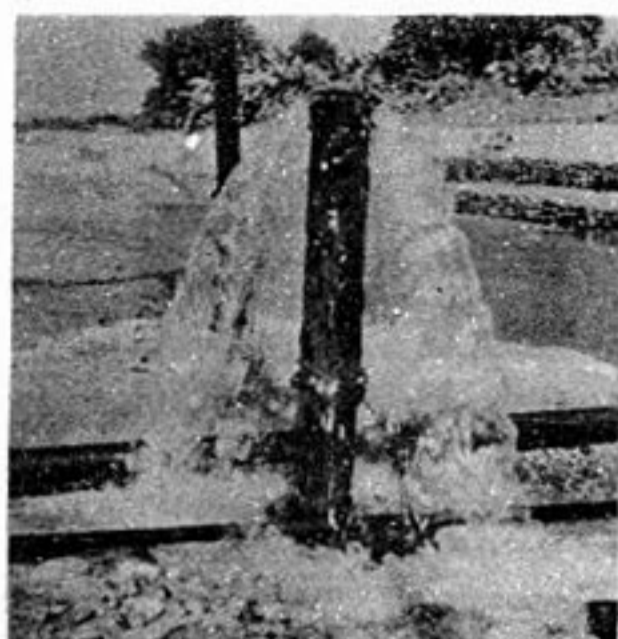


Fig. 2 : Artesian Condition Encountered During Geotechnical Investigation. Photographs show artesian water overflowing from casing and artesian head being measured using standpipe.

floods. Due to the proximity of the area to the hills, rounded to sub-rounded boulders, pebbles and rock fragments that have rolled down the hills are deposited in the area.

The rivers are prone to flash floods during which there is high discharge. The flood waters bring along with it substantial soil and pebbles/boulders as well as tree trunks etc. which are deposited in the Terai plains.

There is substantial flow of the 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. Due to underground flow, the artesian condition is not static but shifts with time. It is equivalent to a flowing underground river and should be treated as hydrodynamic aquifer.

GEOTECHNICAL INVESTIGATIONS

The boreholes were progressed by mechanized heavy-duty percussion type rigs using shell. Chiselling was done to penetrate through the boundary strata and hard clays. Flush threaded casing pipes of 150 mm ID were lowered by rotation and hammering. The casing pipe was kept above the boring level so as to avoid disturbance during sample collection.

The casing was lowered down to the top of the layer in which artesian condition was encountered. To measure the artesian pressure as head above ground level, a closed ended casing head fitted with a nozzle was fixed on the casing top. Over the nozzle, standpipe was attached and supported with the help of a drill rod. The water, due to artesian pressure, rises in the stand pipe and the level of water above ground level was recorded. This gives the artesian pressure at that level at the time of making the measurement. The artesian flow was also measured as a discharge in litres per minute at ground level. Fig.2 presents photographs illustrating the artesian flow and its measurement.

After the measurements the casing is driven down beyond the artesian layer to proceed with further exploration work.

STRATIGRAPHY

Cross sectional profiles based on the investigation at three river locations are presented here. These sections present the distribution of the strata across the river along the bridge alignment. The artesian head measured as height of the water column above the ground level at the borehole location at the time of the investigation is also shown on these illustrations.

River Shivganga

Fig.3 presents the sectional profile across River Shivganga.

Table 1 presents details of the artesian head recorded at the borehole locations during the period of our investigation.

Table 1: River Shivganga : Artesian Head & Discharge Measurements.

Borehole No.	Depth of Strata with artesian pressure, m	Measured Artesian Head above GL, m	Measured Discharge of water at GL, lit/min	Date of Measurement
APP-1	19.5-21.2	3.55	33.3	30.07.96
A-1	19.5-20.6	Minor		16.08.96
	23.5-27.0	7.6	218.2	20.08.96
	33.0-36.5	9.5	800.0	23.08.96
		11.0	1000.0	23.08.96
P-1	During Drilling : No Artesian			
	After withdrawing casing : Water overflowing from hole			15.10.96
P-2	12.0-15.0	Minor		08.10.96
	18.5-22.0	6.15	188.9	08.10.96
	25.0-29.5	8.1	292.3	10.10.96
P-3	8.0-13.5	Minor		10.10.96
	19.7-29.5	4.8	120.0	15.10.96

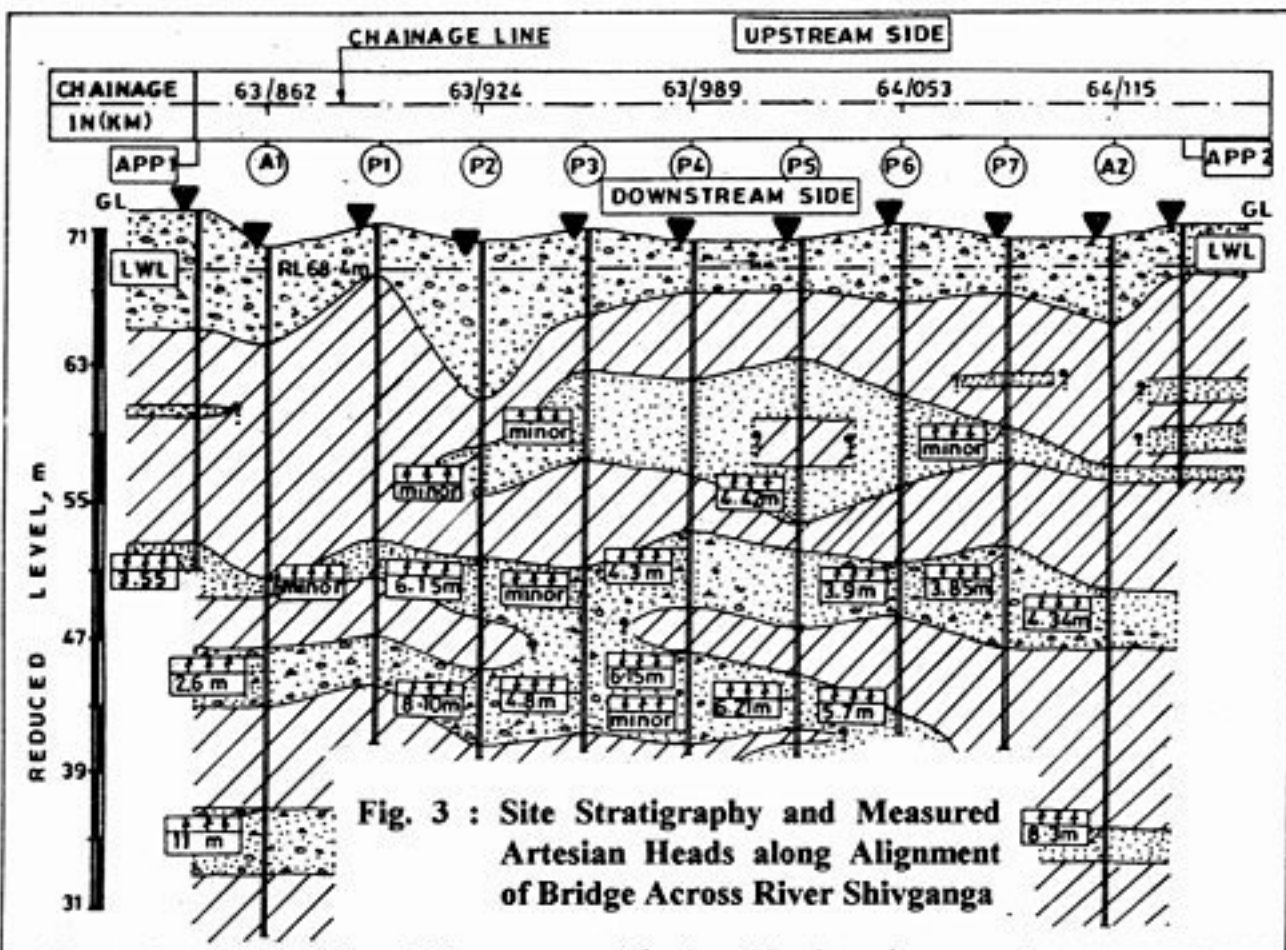


Fig. 3 : Site Stratigraphy and Measured Artesian Heads along Alignment of Bridge Across River Shivganga

LEGEND	
SYMBOL	DESCRIPTION
	PEBBLES & BOULDERS WITH FINE SAND
	SAND WITH PEBBLES & BOULDERS
	SANDY SILT & CLAYEY SILT
	ARTESIAN HEAD ABOVE GROUND LEVEL
	WATER TABLE

(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.

Table 1 (contd.) : River Shivganga - Artesian Head and Discharge Measurements.

Borehole No.	Depth of Strata with artesian pressure, m	Measured Artesian Head above GL, m	Measured Discharge of water at GL, lit/min.	Date of Measurement
P-4	13.6-19.0	4.3	67.7	03.08.96
	24.0-29.5	6.15	184.0	04.08.96
P-5	18.0-23.0	4.42	117.0	25.07.96
	25.5-29.0	6.21	794.0	06.08.96
		5.23	623.0	06.08.96
P-6	20.0-23.0	3.9	60.0	15.07.96
	28.5-30.0	5.7	150.0	18.07.96
P-7	11.0-13.0	Minor		17.06.96
	18.0-24.0	3.85	60.0	24.06.96
A-2	20.6-24.0	4.34	75.0	04.07.96
	34.5-36.5	8.3	300.0	07.07.96

It may be seen from the above that three confined granular strata with artesian pressure is encountered at this bridge location 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.

River Gauriganga

Fig. 4 presents the section profile across River Gauriganga. The following table presents details of artesian head recorded at borehole locations during the period of our field investigation.

Table 2 : River Gauriganga : Artesian Head & Discharge Measurements.

Borehole No.	Depth of Strata with artesian pressure, m	Measured Artesian Head above GL, m	Measured Discharge of water at GL, lit/min.	Date of Measurement
A-1	14.0-25.0	3.0	146.7	03.08.96
P-1	14.0-16.0	2.75	22.0	09.08.96
P-2	20.5-26.0	Minor		14.10.96
P-3	20.0-23.0	Minor		11.10.96
P-4	12.8-18.3	3.0	22.0	24.07.96
A-2	27.5-29.0	4.4	31.6	09.07.96

At this river crossing, three confined layers with artesian head were recorded during our investigation.

- (i) The first confined sand stratum was encountered below about 12.8 to 14.5 m depth. Artesian head of about 3 m was recorded during our investigation.

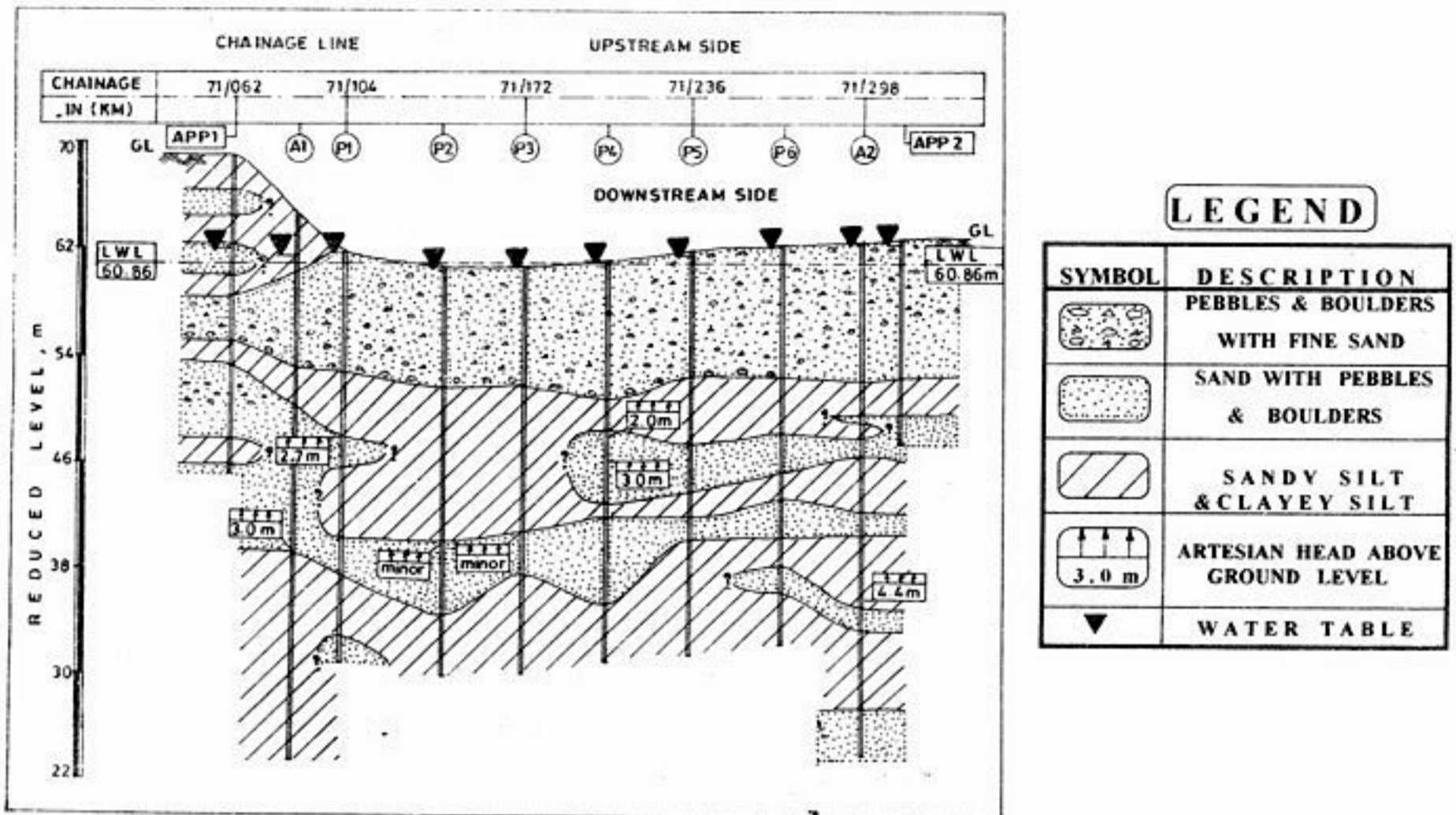


Fig. 4: Site Stratigraphy and Measured Artesian Heads along Alignment of Bridge Across River Gauriganga.

- (ii) A minor artesian head (water overflowing from the top of the casing) was met in the second confined stratum below 19 to 20 m depth.
- (iii) Artesian head of 4.4 m above ground level was met a sand layer at A-2 below 27.5 m depth.

River Karha

Fig. 5 presents the sectional profile across River Karha.

Table 3 presents details of artesian head recorded at the borehole location during the period of our field investigation.

Table 3 : River Karha : Artesian Head & Discharge Measurements.

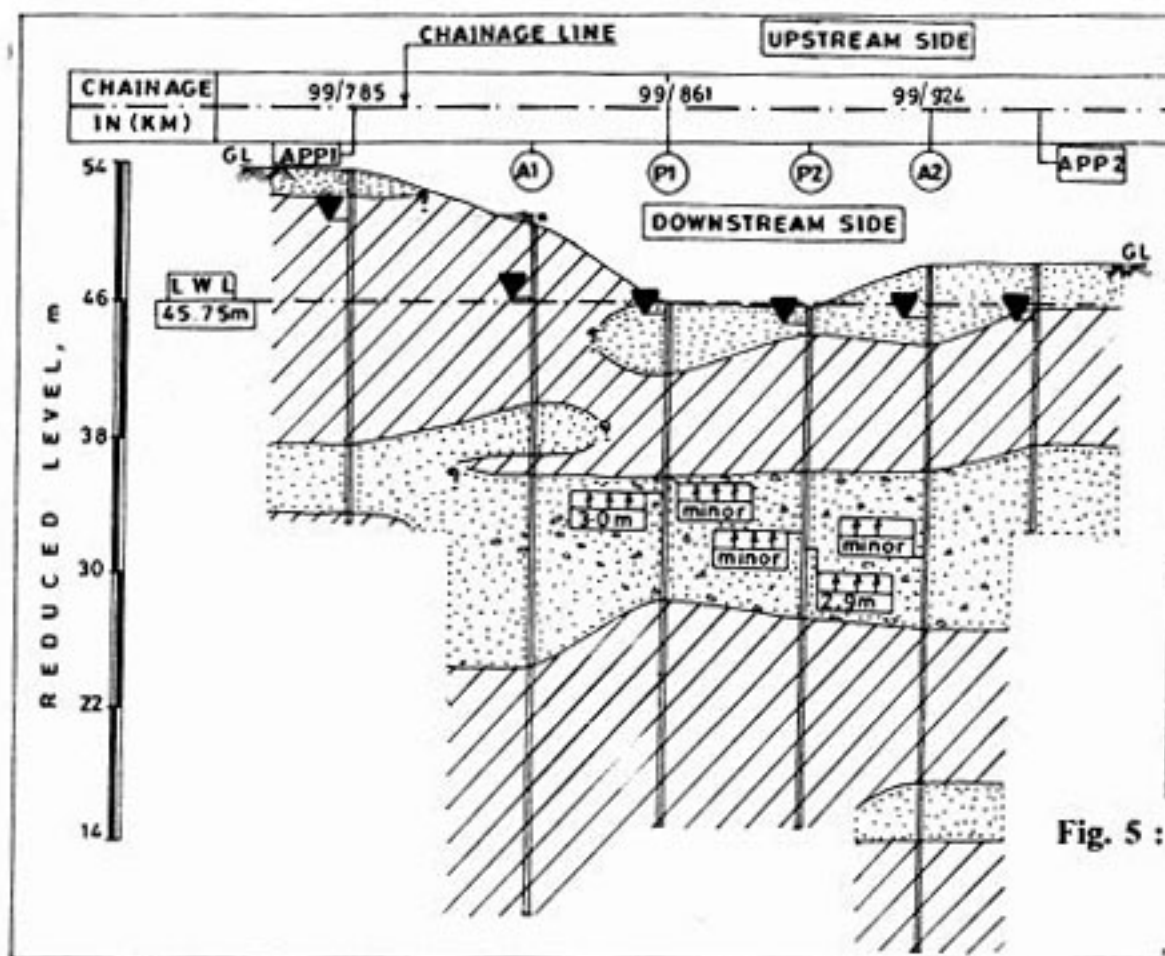
Borehole No.	Depth of Strata with artesian pressure, m	Measured Artesian Head above GL, m	Measured Discharge of water at GL, lit/min	Date of Measurement
P-1	10.0-17.0	3.0	55.0	01.10.96
		3.5	65.0	06.10.96
P-2	09.5-18.0	Minor		10.10.96
		2.9	52.8	13.10.96
A-2	12.0-21.0	Minor		24.09.96

At Karha, a confined stratum with artesian head was encountered below about 9 to 12 m depth. The maximum artesian head recorded as 3.5 m above the ground level. The overflow of water was not observed at boreholes A-1 and APP-1 probably because the ground level was substantially higher. The static water level rose by nearly 4 m at APP - 1 when the borehole was advanced into the sand layer below 16 m depth. This implies a 4 m head of artesian pressure above static water level.

DISCUSSION

The data presented above is based on the geotechnical investigation conducted during the period 1996 - 97 in a stretch of about 70 km of the Kohalpur Mahakali Highway in south western Nepal. Out of nine bridge locations investigated along this stretch, artesian conditions were met at seven locations.

It can be seen from the data presented that 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.



LEGEND	
SYMBOL	DESCRIPTION
	PEBBLES & BOULDERS WITH FINE SAND
	SAND WITH PEBBLES & BOULDERS
	SANDY SILT & CLAYEY SILT
	ARTESIAN HEAD ABOVE GROUND LEVEL
	WATER TABLE

Fig. 5 : Site Stratigraphy and Measured Artesian Heads along Alignment of Bridge Across River Karha.

The artesian pressure has been measured as the height of water column above the ground level at the borehole location. It is apparent that the measured pressure will be a function of the ground level. All the measured artesian pressures should therefore be reduced to a head above a common datum, say the low water level (LWL) of the river.

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 an artesian flow, the static water level in the borehole will rise. Water will overflow from the borehole if the pressure exceeds the hydrostatic head at ground level.

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 strata 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, when the 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 some locations, localized "bed boiling" was observed. Water can be 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.

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 attempts to make a long term assessment. This aspect opens a new avenue for research to work out methodology to assess maximum artesian pressure that may be developed. This may also require new concept of understanding of underground flow characteristics with or without migration of soil particles.

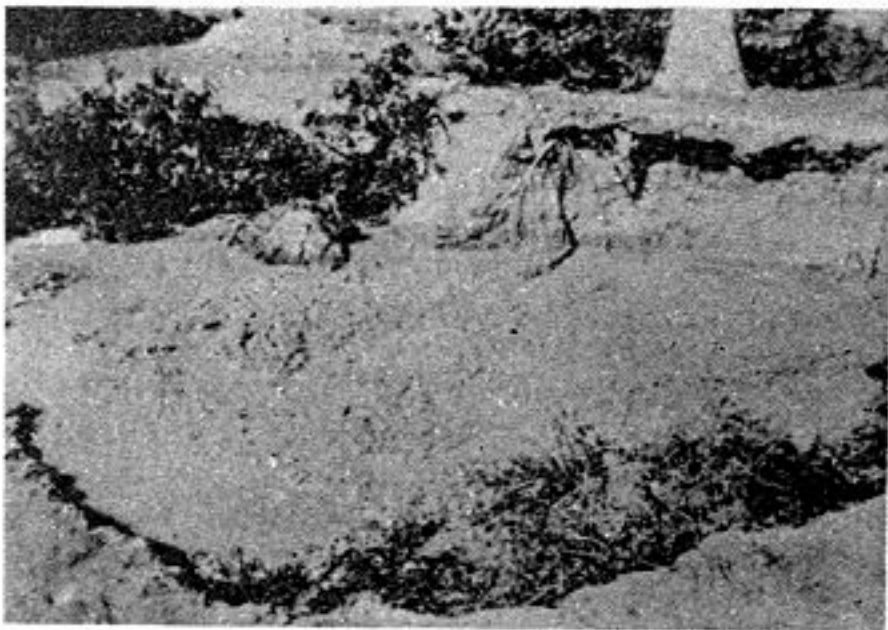
PROPOSED FOUNDATION DESIGN CONCEPT

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 foundations with well tip in clayey strata which is sufficiently above the strata with artesian pressure is a suitable foundation scheme.



(a)



(b)

Fig. 6 : Quick Condition Developed during Geotechnical Investigation. Photograph (a) shows attempt to pull out casing that lost support in strata with artesian flow. Photograph (b) shows quick condition developed due to artesian puncturing through overlying strata after withdrawal of casing.

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.

Design Criteria

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

- (i) The stability of river bed 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.

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 river bed.

Effective overburden pressure at artesian Level = $q' = \gamma_t a - u$

where :

γ_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 below well tip. = [(RL of bed - RL of strata with artesian head) + p]
γ_w	=	unit weight of water
p	=	artesian head above ground level

To protect the bed from boiling ($q' \leq 0$), 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.

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. This may be done by water so as to counter balance the artesian head.

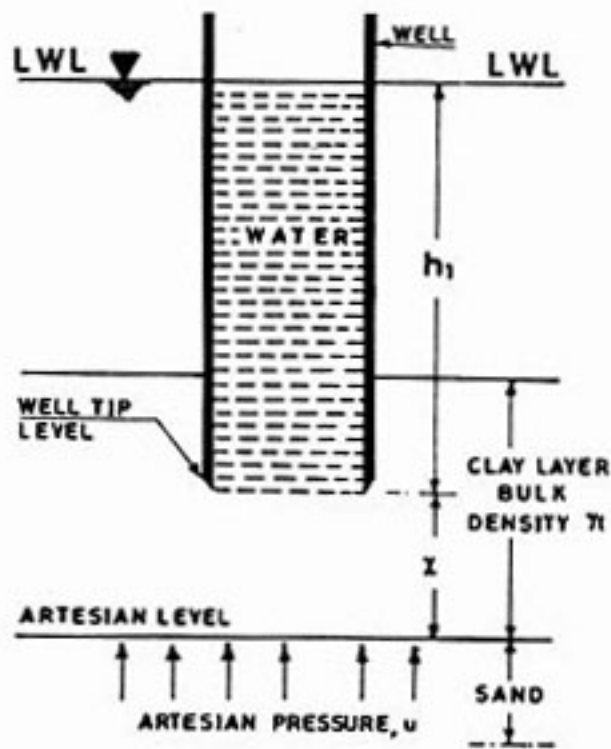


Fig. 7 : Soil Cushion Thickness Above Artesian Level

- h_1 = depth of well tip below ground level.
 γ_w = unit weight of water
 χ = thickness of soil cushion between well tip and underlying sand (artesian level).
 p = highest expected artesian head above G.L.
 γ' = $\gamma_t - \gamma_w$ = submerged density of soil

Downward Pressure = Water head inside well + pressure due to soil cushion
 $= h_1 \gamma_w + \chi \gamma_t$

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

For stability purpose
 $h_1 \gamma_w + \chi \gamma_t \geq (h_1 + \chi + p) \gamma_w$

Hence $\chi \geq p \gamma_w / \gamma'$

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

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.

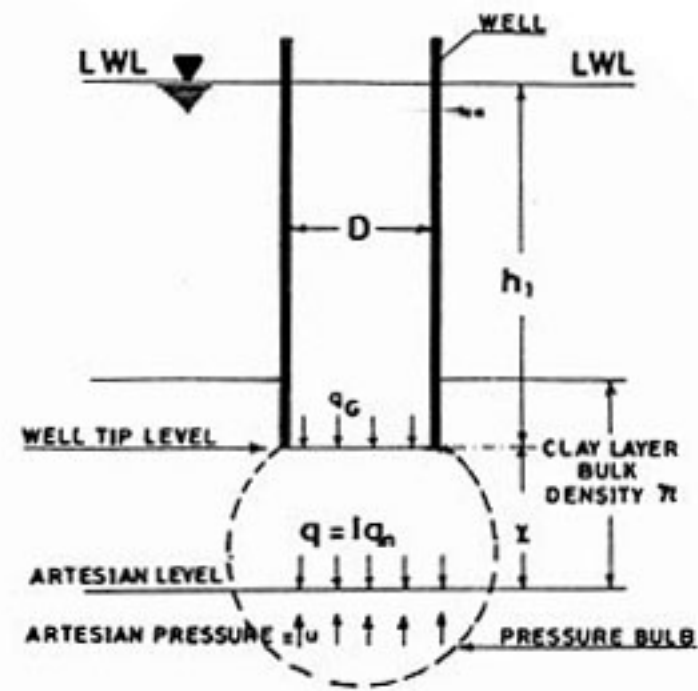


Fig. 8 : Distribution of Stresses Below Well Tip

Gross Applied Soil Pressure at Well Tip : q_g
 Net Applied Soil Pressure at well tip : q_n
 $= q_g - \gamma' h_1$

Effective overburden pressure at artesian level = q'
 $= \gamma_t (h_1 + \chi) - u$

Effective safe gross bearing capacity of artesian layer = q_{ga}
 $= \frac{1}{F} [q' N_q + 0.5 B \gamma' N_\gamma]$

Total stress at Artesian level = 1
 = Superimposed stress (Boussinesq Case) + effective overburden pressure
 $= I_z q_n + \gamma' (h_1 + \chi)$

where
 I_z = Influence factor for circular loaded area at depth χ below well tip.

If effective soil resistance at artesian level (q_{ga}) is less than the effective stress from superimposed loading, the artesian layer will not yield under superimposed loading.

CLOSURE

This paper is an attempt to report the unusual but problematic phenomenon of foundations under artesian condition. The field experiences during the geotechnical investigations, methodology adopted for measuring artesian pressures and discharge and the hitherto unreported phenomenon of "multiple artesian layers" and "shifting of artesian points" are presented. The authors

have put forward the concept of "bed boiling", "minimum soil cushion thickness" and "effective bearing capacities at interface of artesian layers" as a first step to analyse this problem.

Further research is required to make a detailed study of this unique 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. This presentation is but a beginning to an existing and new avenue of geotechnical engineering - **Artesian Conditions**.

ACKNOWLEDGMENTS

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