Advances in Intelligent Systems and Computing

Volume 979

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Hydro-Chemistry for the Analysis of Sub-surface Water Quality in North-Eastern Haryana: A Fast-Urbanizing Region

Sandeep Ravish, Baldev Setia and Surinder Deswal

Abstract Hydro-geochemical characteristics of sub-surface water in the concerned region comprising Yamunanagar and Ambala districts of Haryana, India, were estimated. The hydro-geochemical feature of sub-surface water in the concerned region was investigated by collecting 30 sub-surface water samples. Groundwater samples from specific deposits were analysed for physico-chemical elements, i.e. pH, TDS and prime ion contents, i.e. potassium, sodium, magnesium, calcium, bicarbonate, chloride and sulphate. These ions were as abundance of sodium > calcium > magnesium > potassium, and bicarbonate > chloride > sulphate, respectively. The principal component analysis (PCA) and hydro-geochemical diagrams have been found to be in good agreement in optimizing the significant elements. Analysis of chemical dataset represented that the predominant hydro-chemical facies in the area of study were Na+–HCO3−–Cl− and ‘Ca2+–Mg2+–HCO3–Cl−’ types. Sub-surface water in the area of study is normally very hard, moderately hard and slightly saline in most of the region. Chloro-alkaline indices (CAI) revealed that the most of the water samples showed positive magnitude showing reverse ion exchange process in sub-surface water. Scholler assortment of water pointed out that there was longer residence period of aqua with more prominent base exchange. The outcomes of the appraisals were explained with hydro-geology, and the chemical contents in the sub-surface water vary temporally and spatially. As per the observations of year 2017, 13.33, 66.67% of water samples in TDS, TH, respectively, of the study area are suffering from non-suitability of aqua for drinking and irrigation purposes.

Keywords Sub-surface water · Hydro-geochemistry · Aquifers · Quality
1 Introduction

During the last few decades, there has been a rapid increase in aqua shortage and need for fresh aqua in semi-arid and arid areas due to intense irrigation practices, industrialization, urbanization and population increase in various parts of the globe. In India, most of the people are relying principally on sub-surface water resources for agricultural, industrial, domestic and drinking activities, due to insufficient supply of surface aqua. In India, many cities and myriad large towns derive aqua supply from sub-surface water for discontiguous purposes via large number of private dug wells and also from municipality network. Therefore, knowledge on hydro-geochemistry of fresh aqua is significant to evaluate the pre-eminence of sub-surface water in any rural/urban region or/and basin that impacts the suitability of aqua for industrial, irrigation and domestic purposes. Significant hydro-geologic elements, i.e. biological activity, topographic relief, mineral weathering and precipitation in a concerned study area are significant for hydro-geochemical reactions and controlling recharge responsible for hydro-chemical constituents polluting the sub-surface aqua. Because of the significance of sub-surface water in domestic and in other purposes, its environmental aspects, i.e. pollution transport, have been significantly investigated. Various investigators have studied on pollution of sub-surface water and hydro-geochemical signatures in discontiguous rural/urban as well as in basins that attributed due to human activities principally by domestic and industrial waste aqua and irrigation activities [1]. The aqua pre-eminence may yield knowledge about the inner hydro-geologic atmospheres via which the aqua has circulated. The hydro-chemical variations of rainfall aqua rely on various elements, i.e. human activities, mineral species dissolution and water–soil interaction [2]. The over-exploitation of sub-surface aqua has hazardously influenced its quantity and quality.

In Yamunanagar and Ambala districts (Haryana) environs, the source of about 90% of domestic and agricultural aqua is from sub-surface aqua resources. However, this aqua resource is facing issues including pre-eminence danger in several regions where the exposure to contamination from irrigation and other ion contamination in deep/shallow sub-surface aqua aquifers makes the aqua unsuitable for consumption of human. Land use for agricultural and urbanization activities in the Yamunanagar and Ambala districts vicinity has enhanced at an alarming rate in last few times. In sophisticated multi-layered alluvium deposits, the shallowest Pheratic aquifer is often most susceptible to saline intrusion and most permeable to human contamination. A number of investigations on sub-surface aqua pre-eminence with respect to domestic and agricultural uses have been recorded in discontiguous parts of India [1]. The investigation region is predominantly an irrigation zone with dense irrigation practices and also situated near the hill-cum-plain area. The majority of the inhabitants in this area rely on irrigation (such as agricultural and cultivators workers). Both for domestic and agricultural practices, substantial quantity of sub-surface aqua is consumed in this region. The investigation of sub-surface water samples from a concerned region offers clues to several hydro-geochemical variations that the meteoric sub-surface aqua undergoes before acquiring different hydro-geochemical
signatures. Therefore, this investigation formed the baseline attempt on the hydro-geochemistry or geochemical process of groundwater, suitability of sub-surface aqua resources and aptness for agricultural and domestic in the Yamunanagar and Ambala districts, Haryana region.

2 Materials and Methods

2.1 Region of Study

The Yamuna is the main river of Haryana running from northeast to south-west direction. The study region is principally drained by one perennial river Yamuna in the North-Eastern part of the Yamunanagar district and 03 non-perennial rivers such as Tangri (Dangri), Markanda, Ghagghar and their tributaries. Yamunanagar, Ambala districts and their vicinity are situated at an average elevation of about 255–300 m above the MSL. The study region covers an about 3330 km² region in and around Yamunanagar and Ambala districts and located between the 76° 30' to 77° 28' E longitude and 30° 06' to 31° 35' N latitude (Fig. 1). Geomorphologically, the study region is situated in the north-west part of the Indian subcontinent. Its climate is sub-humid, hot summer, dry and mild winter and subtropical monsoon with a marked seasonal influence. The districts receive about 81% of its annual average precipitation of around 2183 mm from the south-west monsoon during July to September month. In winter, the minimal temperature drops to 6.8 °C, and in summer, the maximal temperature rises to 48.8 °C with the annual average temperature being 24.1 °C. The area of study spreading over 3330 km² is part of the Indo Gangetic plain that comprises sedimentary rocks of tertiary to quaternary alluvium deposits, which occupy the southern and north part of the region [3]. In the region investigated, however, in alluvium formations, the permeable granular zones consist of fine to medium grained sand and occasionally coarse sand and gravel. The aquifers form highly potential aquifers and comprise sand, silt, gravels and kankar associated with clay. The formation of the kankar may be the rainfall of the CaCO₃ from the sub-surface water, and origin of clays, sand and silt is from alluvium deposits. The sand beds without or with kankar in the region form zones of the principal aquifer of the multi tier aquifer network. The deeper -aquifers are in conditions of confined to semi-confined, as benchmarked to shallow sub-surface aqua under Phreatic condition. As stated sooner, the sedimentary deposits occur in almost the overall area and are presented by tertiary and quaternary deposits. Sub-surface water occurs in these deposits under confined conditions as well as under aqua table and is extracted by means of bore wells, bore-cum-dug wells and hand pumps. Both hand pumps and tube wells are used for sub-surface aqua abstraction for discontiguous purposes in the study region. The hand pumps diameter varies from two to eight metre and varies in depth from 19 to 64 m. The usual depth of tube wells varies from 21 to 77 m below sub-surface level. The intensive extraction of aqua due to urbanization elements and
Fig. 1 Groundwater sample location map of the study area with sampling sites
populace increase in Yamunanagar and Ambala presents a decreasing trend of the aqua level in various parts of the perusal region. The availability of sub-surface aqua and nature of occurrence in the perusal region have been monitored by conducting hydro-geologic studies.

2.2 Methodology

Totally 30 sub-surface water samples have been identified and collected in order to represent the whole study area (Fig. 1) from hand pumps and tube wells during April 2017 and appraised to understand the hydro-chemical alterations of ground-water pre-eminence constituents applying standards procedures [4]. Acid-washed (precleaned) polyethylene bottles of one-one litre capacity were applied for the collection of sub-surface aqua samples. Entire sub-surface aqua samples were appraised for total dissolved solids (TDS), pH, prime anions and cations. TDS (HACH, HQ40d) and pH (EUTECH Instruments pH meter pH-700) were appraised applying portable meters. Magnesium (Mg\(^{2+}\)) and calcium (Ca\(^{2+}\)) were measured by ethylenediaminetetraacetic acid (EDTA) titrimetric method. Bicarbonate (HCO\(_3^-\)) and also chloride (Cl\(^-\)) were measured by titration methods. Potassium (K\(^+\)) and sodium (Na\(^+\)) were determined by flame photometer EI-380. SO\(_4^{2-}\) (Sulphate) determinations were measured by the spectrophotometer HACH DR-2800. The hydro-chemical appraisal accuracy was tested by computing ion balance error percentage (IBEP) where the errors in the groundwater samples were usually within 5% [5, 6]. Further, principal component analysis (PCA) using statistical package for social sciences (SPSS) V20.0 and geochemical plots was used to optimize the significant parameters, which are mainly responsible for regulating the hydro-geochemistry of sub-surface water in the investigation region. In this study, 16 elements (pH, TDS, TA (Total Alkalinity), TH, Cl, SO\(_4^{2-}\), CO\(_3^-\), HCO\(_3^-\), Na, K, Ca, Mg, F, NO\(_3^-\), Fe, Cr) were determined but after applying PCA nine elements were resulted to be significant (i.e. eigen value > 1.0 or more and having strong positive loading > 0.50). The PCA analysis yielded nine principal components (pH, TDS, Ca, Mg, Na, K, HCO\(_3^-\), SO\(_4^{2-}\), Cl) with higher eigen values, accounting for 100% of the total variance. Hence, majority of the hydro-geochemical elements (100%) loaded under pH, TDS, TA (Total Alkalinity), TH and Cl were having strong positive loading (0.75), and these were principally responsible for regulating the water chemistry of sub-surface aqua in the investigation region.

3 Results and Discussion

Minimum and maximum levels for the hydro-chemical constituents of sub-surface water are presented in Table 1, benchmarked with BIS guidelines. The profusion of metals is in the following sequence: sodium > calcium > magnesium > potassium and bicarbonate > chloride > sulphate, respectively. Hydro-geochemical diagrams
Table 1 Maximum and minimum levels of the hydro-chemical composition of sub-surface water samples

<table>
<thead>
<tr>
<th>Elements</th>
<th>Range</th>
<th>BIS 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.07–8.12</td>
<td>6.5–8.5</td>
</tr>
<tr>
<td>TDS</td>
<td>220–2770</td>
<td>500–2000</td>
</tr>
<tr>
<td>Ca^{2+}</td>
<td>36–188</td>
<td>75–200</td>
</tr>
<tr>
<td>Mg^{2+}</td>
<td>4.80–88.80</td>
<td>30–100</td>
</tr>
<tr>
<td>Na^{+}</td>
<td>8.5–521</td>
<td>*</td>
</tr>
<tr>
<td>K^{+}</td>
<td>0.0–20.9</td>
<td>*</td>
</tr>
<tr>
<td>HCO_{3}^-</td>
<td>244–1061.40</td>
<td>*</td>
</tr>
<tr>
<td>SO_{4}^{2-}</td>
<td>18–460</td>
<td>200–400</td>
</tr>
<tr>
<td>Cl^{-}</td>
<td>56.80–766.80</td>
<td>250–1000</td>
</tr>
</tbody>
</table>

All the concentrations are in milligram per litre except pH; *Well-being-based standards concentrations have not been established

were also applied to optimize the prime reactions/processes that exert a control over the hydro-geochemical composition of the sub-surface water.

3.1 Hydro-Chemical Indices

Piper plots [7] are employed by delineating the ratios (in meq) of the prime anions (SO_{4}, Cl, HCO_{3}, CO_{3}) on one triangular plot, the ratios of the prime cations (K, Na, Mg, Ca) on another and superimposing the dataset from the two triangles on a quadrilateral. The location of this delineating points out the relative composition of sub-surface aqua in terms of the cation–anion groups that correspond to 04 vertices of the zone. The hydro-geochemical assessment can be explained from the Piper diagram (Fig. 2). The sub-surface water samples were taken from Yamunanagar and Ambala districts of N-E Haryana, India.

Hydro-geochemical constituent of aqua varies in space and period due to hydro-geochemical processes between the porous medium and the aqua and due to variations in patterns of flow and composition of recharge. Such alterations in hydro-chemical signature are applied to subdivide a hydrosome into ‘hydro-chemical indices’ or ‘characteristic fields’ [8]. In the investigation region, the majority of the sub-surface aqua samples were concentrated in the ‘calcium-magnesium-bicarbonate’, ‘sodium bicarbonate’ and ‘sodium chloride’ type (Fig. 2), pointing the mixed water type, hard water and slightly saline nature of the sub-surface water. In usual, a gradual rise of the sub-surface aqua mineralization and shift from the predominant anion bicarbonate through sulphate to chloride are found in aqua flowing from shallow to greater depth, due to increasing rock–water interaction and decreasing sub-surface aqua circulation.
3.2 Hydro-Chemical Process Assessment

A hydro-geochemical plot suggested by Chadha’s [9] has been employed in this investigation to evaluate/optimize the hydro-geochemical processes occurring in the concerned region (Fig. 3).

Datasets were modified to % reaction concentrations (meq %) and shown as the difference between strong acidic anions (SO$_4^{2-} + \text{Cl}^-$) and weak acidic anions (CO$_3^{2-} + \text{HCO}_3^-$) and the difference between alkali (K$^+ + \text{Na}^+$) and alkaline earths (Mg$^{2+} + \text{Ca}^+$) metals for cations. The hydro-geochemical processes recommended by Chadha’s [9] are pointed in each of the four zones of the diagram. These are extensively grouped as: Zone 1: sodium bicarbonate type of base ion exchange aquas, Zone 2: sodium chloride type of end-member aquas (sea aqua), Zone 3: Ca$^{2+}$–Mg$^{2+}$–Cl$^-$.
The most of the sub-surface aqua samples fall in Zones 1 (Na–HCO_3) and 4(Ca–Mg–HCO_3) recommending that the aqua represents type of base ion exchange and recharging water and a few of water samples fall in Zone 2 (end-member water). Zone 3 (Ca–Mg–Cl) aquas are less prominent in the investigation region. Zone 4 (Ca–Mg–HCO_3) aquas are more significant in the concerned region. It may be probably attributed when aqua percolates into the sub-surface from the surface, and it carries hydro-geochemically mobile calcium and the dissolved CO_3 in the form of bicarbonate.

Figure 4 presented the distribution of \((\text{Ca}^{2+} + \text{Mg}^{2+})/\text{HCO}_3^-\) ratio to pH. pH estimates the CO_3\(^{2-}\) nature exist in aqua as CO_3, bicarbonate and H_2CO_3\(^{-}\), in acidic to basic pH stages. The study area pH showed alkaline condition. The gradual rise of pH may be due to the elevated content of hydroxyl ions (H\(^+\)) presence in the concerned region. This may be due to non-availability of neutralizing ions or strong ion exchange complex by clay minerals with cation. This process also aids us to determine circulation of the hydroxyl ions in the sub-surface aqua. Elevated content of H\(^+\) ions present in alluvium aquifers is neutralized by the process of dissolution and weathering. The sub-surface water from the investigation region mostly showed the \((\text{Ca} + \text{M})/\text{HCO}_3\) proportions below 1.0 in all the water samples. Water samples with lower proportions indicated additional bicarbonate input from albite mineral weathering, rather than from calcium and magnesium formation processes alone.

The mK + mNa – mCl versus mMg + mCa – mSO_4 relationship gives information on the hydro-geological sources of Mg and Ca in the groundwater. To pose for meteoric calcium from the dissolution of CaSO_4, an amount of calcium equal to the content of sulphate is subtracted from the sum of alkaline earths metals (magnesium + calcium). Computation of sodium levels depletion posed by exchange of cation was done by supposing that all meteoric sodium inputs were from sodium.

![Fig. 4 Distribution of pH to (Ca + Mg)/HCO_3 ratio](image)
chloride. Because all chloride metals are meteoric in origin, subtracting chloride from the total sodium estimates the meteoric sodium concentration. Figure 5 showed the distribution of \((Ca + Mg)/HCO_3\) and \((Na + K)/HCO_3\). It is to be recorded that the ‘X-axis’ traversed the ‘Y-axis’ at 0.90, i.e. the line along which (sodium + magnesium)/bicarbonate is equal to 0.90. The plot showed higher ratio of \((Ca + Mg)/HCO_3\) and \((sodium + potassium)/bicarbonate\), with calcium + magnesium – bicarbonate – sodium + potassium aqua-type (Fig. 5). The figure displayed the predominance of excess calcium + magnesium and higher sodium + potassium. This displayed that the region has predominance of excess calcium + magnesium and sodium + potassium, with no important impacting anions indications due to pollution.

Most of the sub-surface water samples in the concerned region, showing Ca–Mg–Na–K–HCO_3 water type (Fig. 5). This recommends that silicates minerals weathering is the important contributors to the hydro-chemistry of the study area.

4 Quality of Water

4.1 Quality of Domestic Water

The hydro-chemical characteristics related to the water salinity can be evaluated/optimized by the assessments of the following elements: Cl content and TDS. Desjardin [10] grouped water typology pursuance to the total dissolved solids concentration. Table 2 clearly showed that the higher presentations of the sub-surface aqua samples in the area of study were observed in freshwater and moderately fresh-brackish water types. Salinity occurs in sub-surface water due to anthropogenic sources, leaching from topsoil, weathering of rocks and along with minor climate
Table 2  Water typology according to their content of TDS [10]

<table>
<thead>
<tr>
<th>Type of water</th>
<th>Limit (mg/l)</th>
<th>Number of water samples</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slightly brackish aqua</td>
<td>1000–5000</td>
<td>04</td>
<td>13.33</td>
</tr>
<tr>
<td>Moderately fresh-brackish aqua</td>
<td>500–1000</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Freshwater</td>
<td>&gt;500</td>
<td>11</td>
<td>36.67</td>
</tr>
</tbody>
</table>

impact [11]. The concentration of sodium and bicarbonate in agriculture sub-surface water influences the area drainage and the soil permeability [12, 13].

4.2 Total Hardness (TH)

TH is expressed as the sum of content of their metals defined in milligram per litre of calcium carbonate. TH increases from metals mixed in aqua. TH is applied as the scale formation rate indicator in hot aqua heaters in low-pressure boilers. The United States of Geological Survey TH [14] showed four classes of hardness: very hard, moderately hard, slightly hard and soft. Depositions and scaling issues in air-conditioning plants are accounted with the TH of aqua. The TH of greater than one hundred eighty milli gram calcium carbonate per litre can be categorized as ‘very hard’ aqua and can pose to scaling issues in air-conditioning plants [15]. In the concerned region, 30% of water samples were ‘moderately hard group’, 3.33% fall under ‘slightly hard group’ and 66.67% are in the ‘very hard group’ (Table 3).

Table 3  Hydro-geochemical classification summary

<table>
<thead>
<tr>
<th>Class</th>
<th>Range (mg/l)</th>
<th>Number of samples (30)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS hardness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very hard</td>
<td>&gt;300</td>
<td>20</td>
<td>66.67</td>
</tr>
<tr>
<td>Moderately hard</td>
<td>150–300</td>
<td>09</td>
<td>30.00</td>
</tr>
<tr>
<td>Slightly hard</td>
<td>75–150</td>
<td>01</td>
<td>03.33</td>
</tr>
<tr>
<td>Classification of chloride [18]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brackish</td>
<td>8.46–28.20</td>
<td>02</td>
<td>06.67</td>
</tr>
<tr>
<td>Fresh brackish</td>
<td>4.23–8.46</td>
<td>03</td>
<td>10.00</td>
</tr>
<tr>
<td>Fresh</td>
<td>0.84–4.23</td>
<td>25</td>
<td>83.33</td>
</tr>
<tr>
<td>Very fresh</td>
<td>0.14–0.84</td>
<td>00</td>
<td>00.00</td>
</tr>
<tr>
<td>Base-exchange indices (BEI) Scholler [16]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(sodium + potassium) g.w. → (calcium/magnesium) rock</td>
<td>15</td>
<td>50.00</td>
<td></td>
</tr>
<tr>
<td>(sodium + potassium) rock → (calcium/magnesium) g.w.</td>
<td>10</td>
<td>50.00</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Base-Exchange Index (BEI)

Scholler [16] suggested a term known as ‘Base-Exchange Index’ (BEI) to interpret the hydro-geochemical processes taking place in sub-surface water. There are substances which exchange and absorb their ions with ions existing in sub-surface water. Those substances are known as ‘permutolites’, e.g. organic substances and clay minerals like zeolites, glauconite, halloysite, chlorite, illite and kaolinite. Halloysite, chlorite, illite and kaolinite are the clay minerals in which metals capacity of ionic exchange is low and is present at edges. This condition is reverse in vermiculite and montmorillonite. However, when the number of metals present on the surface is more, the exchange capacity is higher. Indices of chloro-alkaline, CAI1 and CAI2 are applied to estimate the extent of base exchange during interaction of water–rock using Eqs. 1 and 2 [16].

\[
\text{Chloro-alkaline-indices 1} = \frac{[\text{chloride} - (\text{sodium} + \text{potassium})]}{\text{chloride}} \\
\text{Chloro-alkaline-indices 2} = \frac{[\text{chloride} - (\text{sodium} + \text{potassium})]}{\text{ sulphate} + \text{bicarbonate} + \text{carbonate} + \text{nitrate}}
\]

(All metallic content is represented in milliequivalent per litre.)

Where there is no exchange of potassium (K\(^+\)) and sodium (Na\(^+\)) in sub-surface aqua with calcium (Ca\(^{2+}\)) or magnesium (Mg\(^{2+}\)) in alluvium/rock, both the indices are positive and vice versa. In most of the samples, reverse ion exchange is the predominant process in the area of study. The base-exchange indices point that there is a prominent exchange of sodium + potassium in sub-surface water into the calcium + magnesium in alluvium from the matrix, whereas the vice versa is less important and the exchange of sodium + potassium in alluvium to the calcium + magnesium in sub-surface water is less observed [17]. More than 50\% of water samples fall in (sodium + potassium) sub-surface water → magnesium/calcium alluvium and 50\% of the water samples are in (sodium + potassium) alluvium → magnesium/calcium. Chloride classification by Styfzands [18] showed that 19\% of water samples were in the ‘brackish category’, 10\% were under the ‘fresh-brackish category’, and 83.33\% were fresh in nature in rock (Table 3).

5 Conclusions

Dominance of the anion is in the following sequence: sodium > calcium > magnesium > potassium and that of cations is bicarbonate > chloride > sulphate. The concerned region forms a part of the inland aquifers, and the elevated level of TDS extended from the north-eastern to south-western part influenced by anthropogenic sources, leaching from topsoil, weathering of rocks and along with minor climate impact. Elevated content of total dissolved solids was also found in the, central and
south-western, western, north-eastern, north-western, parts due to the metals leaching. Majority of the sub-surface aqua samples varied from ‘slightly hard’ to ‘very hard’ group. Cl classification by Styfzands showed that all the groundwater samples fall in ‘brackish’ to ‘fresh’ range in the study area. Piper plot showed that ‘calcium-magnesium-bicarbonate’ type is the predominant indices in the sub-surface aqua with few presentations of Na–Cl indicating the recharge and end-members water and showed the mixed water type, hard water and slightly saline nature of the sub-surface water. Chadda’s diagram showed that base ion exchange, recharging water and end-member water are more common in rock, which has more presentations of recharging water polluted samples. The PCA analysis yielded nine principal components (pH, TDS, Ca, Mg, Na, K, HCO$_3$, SO$_4$, Cl) with higher eigen values, accounting for 100% of the total variance. Hence, majority of the hydro-geochemical elements (100%) loaded under pH, TDS, TA (Total Alkalinity), TH and Cl were having strong positive loading (0.75), and these were principally responsible for regulating the water chemistry of sub-surface aqua in the investigation region. TDS is higher and exceeded the guideline ranges for domestic purpose in few of the aqua samples in Yamunanagar and Ambala districts. Few sub-surface aqua samples of the investigation region were not suitable for domestic and drinking purposes, and only few sites needs some kind of treatment for better water quality for the human consumption. Hydro-geochemical diagrams and principal component analysis (PCA) may be helpful to optimize the prime reactions/processes that exert control over the hydro-geochemical composition of the sub-surface water. The present study may be helpful for the execution and planning for quality of water, protection of environment and formulation of policies.

References

Numerical Optimization of Pile Foundation in Non-liquefiable and Liquefiable Soils

M. K. Pradhan, Shuvodeep Chakroborty, G. R. Reddy and K. Srinivas

Abstract Numerical optimization techniques are used widely for different engineering fields. But there are limited applications of this method in geotechnical engineering. However in this study, topology optimization of pile foundation for different site conditions and loading conditions is obtained through a finite element (FE) analysis study. The suitable topology of piles in foundation system offering minimum internal energy, i.e. maximum stiffness for a given fraction of material is studied. The study is also enhanced to the piles which are located in the soils prone to liquefaction. In the present study, the design methodology for cost optimization of construction of a pile group with a raft foundation is also presented through a case study. In the optimization algorithm, the raft dimensions, no of piles, pile diameter, pile length are taken as the design variables.

Keywords Pile foundation · Topology optimization · Liquefaction · Cost optimization

1 Introduction

Pile foundation is used for large number of purposes in geotechnical fields like to cater the heavy load of the structure to harder strata, to support the structure where the uplift force is high, to resist lateral loads, supporting retaining walls, bridge piers, abutments, etc. In general, there are two types of pile, namely driven piles and bored piles. Once the decision for pile foundation has been taken, the engineer must choose the type, topology and size of the pile which is most suitable for a particular soil and loading condition. Using the numerical optimization technique, it will be much easier to obtain the topology of pile foundation which is most suitable and will optimize the material use.
1.1 Topology Optimization of Pile Foundation

When a structure is carrying heavy load and near ground, soil strata are comparatively weak, it is often inevitable to go for pile foundation. At this stage, topology optimization can be conducted which will improve deformational behaviour of structure along with cost-saving, economy in material use. Possible topology of piles under a strip footing may be any one of the followings as depicted in Fig. 1a–d.

Depending on the magnitude and direction of the forces acting on the strip footing and the soil characteristics existing in site, the best suitable pile foundation topology can be established. Further using shape optimization, more knowledge about the suitable shape of that chosen topology can be obtained (Fig. 2a–d).

Further, size optimization may be used to optimize size of pile (Fig. 2a) or the dimensions of varied parts in piles (Fig. 2b–d).

Topology optimization was first used in geotechnical problem for the underground excavation in linear elastic rock material by Ren et al. [1]. Pucker and Garbe [2] presented topology optimization under a strip footing in granular hypoplastic material. In this paper, the application of topology optimization is presented by FE analysis for both liquefiable and non-liquefiable soils under different loading conditions. The FE analysis of topology optimization is based on solid isotropic material with penalization (SIMP) method which is illustrated briefly in Sect. 2.

1.2 Cost Optimization of Pile Foundation with a Raft

In general, the foundation cost of real-world structures can vary from 5 to 20% of the construction cost of the superstructure [3]. For a conservative design, much attention is not paid to cost of the construction of such foundation. Hence, sometime it may happen that the number of pile used in foundation for design is much more than actual requirement and this unnecessary increases cost of the project. Hence, an optimum
design methodology fulfilling all structural criteria should be studied to minimize cost prior to the detail designing of the proposed structure. The main objective is to minimize the pile foundation cost with the consideration of all the constraints like bearing capacity of the soil beneath the raft, pile load-bearing capacity, settlement criteria as in IS: 2911 Part IV [4]. The optimization formulation in the present study is carried out through a case study and is based on the evolutionary algorithm by Lagaros et al. [5].

2 Topology Optimization of Pile Foundation

In FE analysis, the topology optimization is carried out by using a numerical optimization algorithm, i.e. SIMP by Sigmund [6] through an iterative procedure. SIMP method assumes that material is uniformly placed in the design domain. The material property depends on the relative density \( \rho \). The relative density varies over the design domain. It is considered that material is concentrated at highly loaded regions. The relative density should be either zero or one in the design domain after optimization completed. Zero relative density signifies no material and unit value signifies material.

The aim of the optimization procedure is to minimize the compliance, i.e. the internal energy of the structure in the design domain so that stiffness of the structure can be maximized for a given fraction of material in the design domain.

Optimization task is basically,

Minimise: internal energy \( c(x) = U^T K U \) i.e also the objective function (1)

Subject to:

\[ KU = F \]  
\[ V_\delta = V_0 \delta \] These are the constraints. (3)

where \( U \) is the global deformation tensor, \( K \) is the global stiffness matrix and \( x \) is tensor of design parameters. Where \( F \) is the external forces and \( V_0 \) is the initial volume in the design domain, \( V_\delta \) is the volume after optimization and \( \delta \) is fraction of initial volume. The relative density \( \rho \) of the element changes as iteration progresses.

The material change over of material with a relative density \( \rho \) and a chosen penalty term \( p \) from elastic modulus \( E_1 \) to \( E_2 \) is given by Eq. 4.

\[ E_2 = E_1 \rho^p \] (4)
2.1 FE Modelling

Optimized topology of piles is obtained using this method in a 2D-FE analysis with a strip footing for both non-liquefiable and liquefiable conditions of soil under different types of loadings.

2.1.1 In Non-liquefiable Soil

The existing strip footing of 5 m wide and 1 m depth carries both vertical and horizontal loads is resting on a soil of elastic modulus of 70 MPa and poison ratio 0.3. The elastic modulus of concrete is 25,000 MPa. The soil mass continuum of 80 m wide and 60 m deep under the strip footing is considered for developing the numerical model. The design domain is of 20 m wide and 15 m deep as shown in Fig. 3a. The $x$ and $y$ displacement of the soil continuum is restricted in both the $y$ and $x$ plane, respectively. FE analysis has been carried out for both horizontal and vertical loading.

In the present study, the soil and concrete have been analyzed using linear elastic material property. For meshing free mesh control for both soil and strip footing with plane stress, linear element of reduced integration and hourglass control has been chosen. As the design domain is our area of concern, the size of meshing is reduced to capture the results efficiently and is shown in Fig. 3b. For modelling the strip footing and soil, it is assumed that no relative movements occurred between them. Hence they are modelled integrally. The main objective of this modelling is to minimize the stain energy of the whole model by using 10% of the material that is in the design domain. Thus, the optimum topology for pile foundation can be obtained.

![Fig. 3](image-url)
2.1.2 Liquefiable Soil

In this analysis, it is considered that the soil is susceptible to liquefaction under seismic condition. Hence to optimize the topology for the pile foundation for such soils, the post-liquefaction modulus of elasticity has been considered, i.e. generally, one-tenth of initial elastic modulus. As it can be observed in Fig. 4, the soil has been divided into three layers of 10, 20 and 30 m from top to bottom. Considering post-liquefied state in the middle layer, elastic modulus is taken as 7 MPa. Concrete property and other soil layers property has been considered same as described in the earlier section for non-liquefiable soil condition. The geometric condition, boundary condition, element type are identical to the previous section. The analysis carried out for a vertical loading of 500 KN.

2.2 Results and Discussion

Figure 5 depicts the progress of FE analysis in successive iterations by minimizing the strain energy and keeping material fraction 10% of original volume.

It can be observed from Fig. 6a that when there is no eccentricity in loading, a simple vertical profile of pile is obtained. From Fig. 6b, it can be seen that a vertical pile along with an inclined pile be the efficient topology for pile for a vertical and horizontal loading condition. Figure 6c shows the same topology but with a thicker inclined pile is required than the previous one as the horizontal load increases in this case. Nowadays, any profile of piles can be constructed efficiently by concrete jet grouting method. Hence, this method realizes pile construction with any optimized topology. In the case of the liquefiable soil, it remarked from Fig. 6d that the battered pile or inclined pile will be most suitable to provide a very stiff foundation within minimum concrete use. But due to being stiff, the design for induced seismic forces and ductility check under seismic condition is very important to consider.
Fig. 5  Objective function minimization and material fraction versus number of cycles

Fig. 6  Topology optimization under strip footing for 

a  vertical loading, $P = 500$ KN, horizontal loading, $H = 0$ KN in non-liquefiable soil; 
b  $P = 500$ KN, $H = 100$ KN in non-liquefiable soil; 
c  $P = 500$ KN, $H = 250$ KN in non-liquefiable soil; 
d  $P = 500$ KN, $H = 0$ KN in liquefiable soil