H. armigera infestation in pigeon pea. Increased iron content in apoplast after pathogenic fungi attack[14] coupled with a report that nitric oxide mediates iron-induced ferritin accumulation[15] which is involved in protecting plants against oxidative stress[16] and another report indicating upregulation of nitrate and nitrite content which can increase NO production upon *H. armigera* herbivory[17] suggest possible role of iron in plant protection against insect attack. However, the exact role of Fe, hidden under multilayered plant immune responses needs to be unravelled.

In biofortification research, Zn foliar spray has been suggested to enhance grain/seed Zn content[18,19]. The observed negative association between Zn content and insect herbivory prompts us to suggest that such foliar application will not only lead to biofortification of grains/seeds, but may also lead to better protection against insect attacks.

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Design of barrage on heterogeneous and anisotropic soils

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The present study reports on the design of barrages on heterogeneous and anisotropic soils, based on the analysis of subsurface flow by finite element method. The study indicates that the location of impervious layer below the sheet piles marginally changes the uplift pressures, but with an advantage of reduction in the exit gradient. On the contrary, the location of a pervious layer below the sheet piles drastically changes the uplift pressures along with a drastic increase in the exit gradient and therefore, will have a major impact on the design of a barrage. The isotropic and anisotropic soils behave differently under subsurface flow considerations and unlike isotropic soils, the depth of upstream sheet pile/cut-off can be an important factor for the design of a barrage on anisotropic soils. The uplift pressures and exit gradients can be reduced by increasing the depth of upstream sheet pile for anisotropic soils.

Keywords: Barrages, heterogeneous and anisotropic soils, river engineering, waterways and canals.

THE importance of barrages in India in view of the alarming water scarcity is noteworthy[1], as it is used to divert river water through canal system for irrigation and other useful purposes in tropical and subtropical countries. A

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barrage involves huge expenditure and its safe design under various types of subsoil strata is required as most of the studies are available only for homogeneous and isotropic soils. Khosla's concept of barrage design for subsurface flow is normally used in the Indian subcontinent assuming the soil to be homogeneous, isotropic and of infinite extent[2,3]. Garg *et al.*[4] proposed a method for the optimal design of a barrage based on Khosla's[2] concept of barrage design. Many field conditions violate these assumptions[5–7] and there are no studies available in this context. Although finite element has been used to demonstrate its applicability to handle heterogeneity and anisotropy in academic problems[8], no study is available on the design of a barrage on heterogeneous and anisotropic soils. The present communication uses the finite element method to analyse the subsurface flow for heterogeneous and anisotropic soils and gives some useful suggestions for the design of a barrage on account of soil heterogeneity and anisotropy from the designer's point of view.

In barrages/weirs, the subsurface flow will mainly be two-dimensional as the widths of Indian rivers are considerable so that the subsurface flow at any cross-section of the barrage is not appreciably influenced by any cross flow from the sides, except near the flanks. The flow of water through homogeneous and isotropic subsoil below a barrage for a two-dimensional steady state condition obeying Darcy's law is governed by the Laplace equation. The exact solution of the equation is not possible for complex boundary conditions. Khosla[2] used Schwarz–Christoffel transformation to find solutions for a number of simple profiles resting on homogeneous and isotropic soil of infinite extent in vertical and lateral directions.

The subsurface soil profile for Indian rivers can be mostly considered as alluvial. Alluvial soil is composed of alluvium deposits by the rivers. These soils consist of diverse ratios of clay, sand and silt and often have a layered profile, with the depth of each layer determined by the intensity of the flood that deposited the material. These formations are generally heterogeneous and anisotropic as well. Even if the soil is homogeneous, it can be anisotropic with respect to permeability with the coefficient of permeability having a maximum value in the direction of stratification and minimum value in the direction normal to that of stratification. Ratios of horizontal to vertical permeability of 2–10 are not unusual and the ratio can go as high as 500 depending upon type of soil[9]. Therefore in the present study, finite element is used to analyse the subsurface flow to gain insight into the effects of heterogeneous and anisotropic soil on the barrage design.

The standard equation for two-dimensional potential flow with the coefficients of permeability (k_{xx}, k_{yy}) in two directions is solved; the finite element formulation details can be found in any standard book[10]. In order to check the validity of the code before carrying out the detailed analysis, the simplified problems were analysed by the code for which the results were available either by Khosla's theory or by electrical analogy models. A good agreement was found among the results obtained by all these methods.

Often a confining impervious silt/clay layer or a pervious sand layer occurs below a barrage. Therefore in the present study, the problem domain was chosen as a three-layered soil system below a barrage with the middle layer as either a confining impervious layer or a pervious layer (Figure 1). The soil was assumed to be either heterogeneous and isotropic or heterogeneous and anisotropic. The ratio of horizontal (k_{xx}) to vertical permeability (k_{yy}) varies from 5 to 20 for anisotropic soils. The sheet piles or vertical cut-offs were considered at upstream and downstream ends of the floor as intermediate sheet piles are not in vogue, since these are not effective in reducing either the uplift pressures or the exit gradients. Various notations and dimensions are shown in Figure 1, where b is the total length of the floor; b_1 the distance of an intermediate point of the floor from upstream pile; d_1 and d_2 are the depths of upstream and downstream piles respectively; T the distance of the middle layer soil from the bottom of the pile; midt, the thickness of the middle layer of soil; α_1 the ratio of the total floor length b and the upstream pile depth $d_1 = (b/d_1)$; $\alpha_2 = b/d_2$; K_1, K_2 and K_3 are the permeabilities for the heterogeneous and isotropic soils corresponding to the top, middle and bottom layers respectively, and k_{xx} and k_{yy} are the coefficients of the permeability in the x and y directions respectively, for the anisotropic soil.

The boundary conditions are also shown in Figure 1. The boundaries *rstuvw* and *qpyx* were taken as the innermost and outermost streamlines respectively, implying no flow across them. The piezometric head ϕ was fixed as 100% on the upstream side of the floor, i.e. *qr* and 0% on the downstream side of the floor, i.e. *wx*. The effective depth of soil strata below the sheet pile was taken as maximum of five times the depth of sheet pile and two times the width of the floor. The effective lateral soil

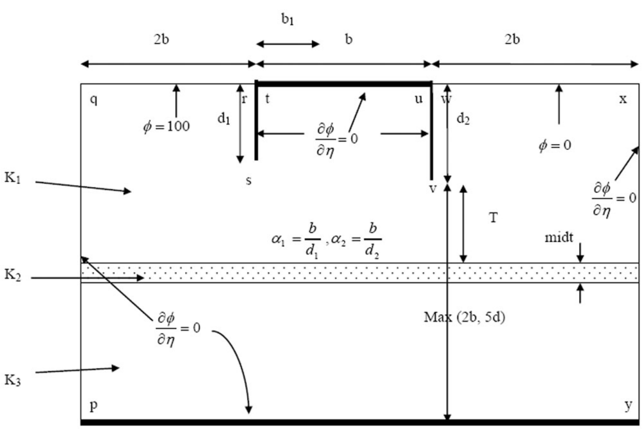

Figure 1. Problem domain indicating various notations and boundary conditions.

reaches beyond the upstream and downstream sides of the floor were taken as two times the width of the floor. The effective boundaries in vertical and lateral directions were fixed on the basis of previous studies[11–14], such that it had only a slight influence on the potential distribution near the structure. The problem domain was discretized into 1584 quadratic isoparametric serendipity elements. The area was modelled such that the density of the elements was kept higher in the area closer to the piles and below the floor compared to that of the elements beyond it. Also, a dense mesh was chosen for the middle layer and around it.

The confined seepage analysis below the floor was carried out for various α_1 and α_2 values for the problem domain shown in Figure 1, but the trends were found to be similar for different α values. The same trends were also obtained for different barrage profiles corresponding to three-layered soil system below the barrage, but it is explained with reference to Figure 1. Only limited figures are shown due to paucity of space and the results are discussed from the designer's point of view.

The behaviour of the middle layer, either an impervious layer or a pervious layer, was found to be dependent upon its permeability relative to the upper soil layer. The thickness, permeability and location of the middle layer were varied and the effect on the uplift pressures and exit gradients was determined. The results indicated that if the middle layer is around 1000–10,000 times less pervious compared to upper layer, then it would behave as impervious irrespective of its thickness; if the middle layer is around 1000–10,000 times more pervious compared to upper layer, then it would behave as pervious irrespective of its thickness. The results also remained insensitive to the permeability values (K_3) of the bottom layer within these ranges of the permeability of the middle layer, irrespective of its thickness and location. The ranges were also found to be valid for anisotropic soils. Therefore, these ranges of the permeability, corresponding to impervious or pervious layer, were assumed for the middle layer while carrying out further analysis.

An analysis was then performed to find out the effect of location of the impervious or pervious layer below the sheet pile on the uplift pressure and exit gradient. It was found that the location of impervious layer below the piles marginally changed the pressure distribution for both the isotropic and anisotropic soils. The exit gradients reduced for both the isotropic and anisotropic soils as the distance of the impervious layer below the pile was reduced. For example, the uplift pressures for equal piles ($\alpha_1 = \alpha_2 = 6$) were increased from 67.44% to 72.33% at the upstream end of the floor and were decreased from 32.55% to 28.8% at the downstream end of the floor for the isotropic soils as the distance of the impervious layer was reduced from $T = 2b$ to $T = 0.1b$. Further, for anisotropic soils there was hardly any change in the uplift pressures and with $k_{xx}/k_{yy} = 5.0$, the uplift pressures were increased from 58.53% to 59.87% at the upstream end of the floor and were decreased from 41.47% to 40.13% at the downstream end of the floor. The corresponding values were 52.5% to 52.51% and 47.75% to 47.49% for $k_{xx}/k_{yy} = 20.0$ as the distance of the impervious layer was reduced from $T = 2b$ to $T = 0.1b$. As the anisotropy increases, the head loss is mainly in the vertical direction, thus making the pressure line to around 50% throughout the floor length. The exit gradients reduced for both the isotropic (2.75–1.72) and anisotropic soils (3.31–2.45 and 3.55–2.96) as the distance of the impervious layer below the pile was reduced.

However, unlike clay layer, the results showed a drastic change in the pressure distribution and exit gradient below the floor for the pervious layer. For example, the uplift pressures for equal piles ($\alpha_1 = \alpha_2 = 6$) were reduced from 67.44% to 53.03% at the upstream end of the floor and were increased from 31.13% to 46.97% at the downstream end of the floor for the isotropic soils as the distance of the pervious layer was reduced from $T = 2b$ to $T = 0.1b$. Further, for anisotropic soils there was not much change in the uplift pressures and with $k_{xx}/k_{yy} = 5.0$, the uplift pressures were reduced from 58.53% to 52.40% at the upstream end of the floor and were increased from 41.47% to 47.60% at the downstream end of the floor. The corresponding values were 52.5% to 50.91% and 47.75% to 49.09% for $k_{xx}/k_{yy} = 20.0$ as the distance of the impervious layer was reduced from $T = 2b$ to $T = 0.1b$. Contrary to the impervious layer, the exit gradients increased drastically depending upon the location of the pervious layer. The exit gradients increased from 2.75 to 5.71 for isotropic soil, 3.31 to 5.74 for $k_{xx}/k_{yy} = 5.0$ and 3.55 to 5.74 for $k_{xx}/k_{yy} = 20.0$ as the distance of the pervious layer was reduced from $T = 2b$ to $T = 0.1b$. Therefore, safety has also to be ensured against piping because of the increased exit gradients besides the uplift.

Hence the location of the pervious layer will have a major impact on the thickness of the floor for isotropic soils to counter the uplift pressures as the uplift is increased on the lower portion of the floor. There was only marginal effect on the pressure distribution for anisotropic soils because it was already approximately 50% depending upon the level of anisotropy. However, the exit gradients were drastically increased for isotropic as well as anisotropic soils. Therefore, the location of pervious layer below piles will have a major impact on the design of the floor for isotropic as well as anisotropic soils.

The subsurface flow can be further best explained with the help of flownets. The flownets are drawn corresponding to two equal piles ($\alpha_1 = \alpha_2 = \alpha = 6$) and the equipotential lines in all the flownet diagrams are drawn at an interval of 5%. Figure 2 *a* shows the equipotential and streamlines for homogeneous isotropic soil. Figure 2 *b* and *c* shows the flownets corresponding to isotropic soil with an impervious layer and pervious layer at $T = 0.1b$ below sheet piles respectively. While most of

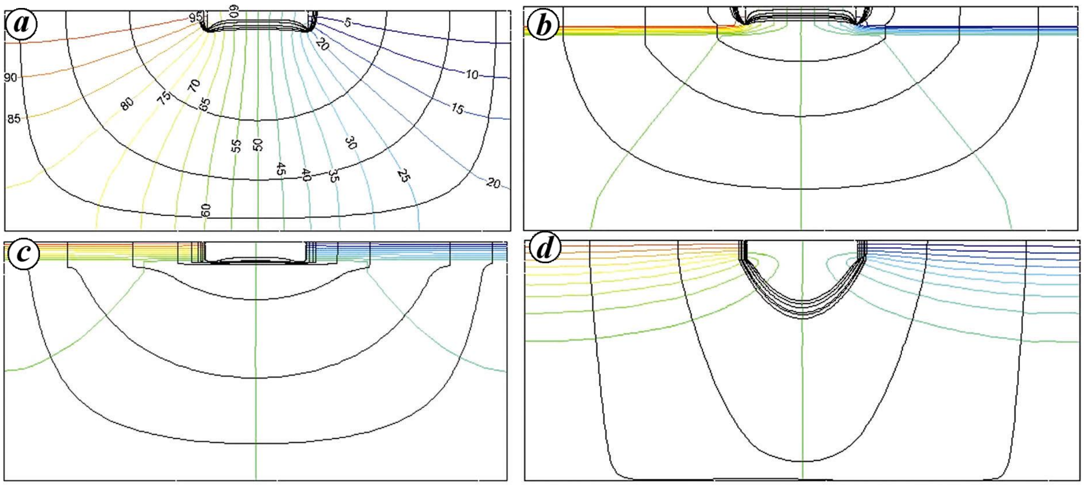

Figure 2. Flownets for two equal piles ($\alpha = 6$); equipotential lines are drawn at an interval of 5% for all the flownets. ***a***, Homogeneous isotropic soil; ***b***, Isotropic soil with impervious layer at $T = 0.1b$; ***c***, Isotropic soil with pervious layer at $T = 0.1b$; ***d***, Homogeneous anisotropic soil with $k_{xx}/k_{yy} = 20$.

the equipotential lines are concentrated in the impervious layer (Figure 2 *b*) because of the head loss across the impervious layer, Figure 2 *c* shows that the equipotential lines remain mainly confined above the pervious layer as the head loss is primarily up to the pervious layer. Figure 2 *d* shows the flownet for homogeneous anisotropic soil with $k_{xx}/k_{yy} = 20.0$. Unlike Figure 2 *a*, it can be seen from Figure 2 *d* that the head loss is now primarily across the upstream and downstream piles.

Further, the behaviour of anisotropic soils is found to be different than isotropic soils. The values of exit gradients for homogeneous isotropic and homogeneous anisotropic soils are plotted in Figure 3 *a* for different α_1 and α_2 values. It is evident from Figure 3 *a* that the exit gradients are not sensitive to α_1 values for isotropic soils, but are sensitive to α_1 values for anisotropic soils. The results also reveal that the exit gradients for the anisotropic soils can be brought down to the level of isotropic soils by reducing α_1 for the same value of α_2. For example, in Figure 3 *a*, the exit gradients corresponding to $\alpha_1 = 24$ and $\alpha_2 = 12$ can be found as 4.67 and 7.13 for isotropic and anisotropic soils respectively. α_1 can be reduced to 3 by increasing the depth of upstream pile while keeping the depth of downstream pile to be the same, i.e. $\alpha_2 = 12$. The new exit gradients corresponding to $\alpha_1 = 3$ and $\alpha_2 = 12$ can be found as 4.02 and 3.75 for isotropic and anisotropic soils respectively (Figure 3 *a*). It can be noted that there is significant reduction in the exit gradient for the anisotropic soil and the exit gradient is reduced even below the isotropic soil just by increasing the depth of upstream pile.

Figure 3 *b* shows the variation of uplift pressures with distance for $\alpha_1 = 3$ and $\alpha_2 = 12$ for both the isotropic and anisotropic soils. It can be seen from Figure 3 that along with a reduction in exit gradient by increasing the depth of upstream pile, there is an additional advantage of a significant reduction in the uplift pressures on the entire floor for anisotropic soils compared to isotropic soils. Therefore, unlike isotropic soils, the depth of upstream sheet pile must be increased to reduce the uplift pressures as well as exit gradient for the anisotropic soils and can be an important factor for an economical design of a barrage on anisotropic soils.

It may also be worthwhile to mention that Khosla[2] considered that the exit gradient can be controlled either by increasing the depth of the downstream pile or by increasing the total floor length as upstream pile was not found to be effective in controlling the exit gradients. But the same is not true for anisotropic soils. It may be noted from previous discussions that both for isotropic soils with sand layer below piles and anisotropic soils, the head loss is primarily in the vertical direction and therefore, the exit gradients cannot be reduced merely by increasing the length of the impervious floor. Therefore, even after applying high factors of safety as suggested by Khosla, the exit gradients may work out to be more for anisotropic soils. Another problem can be seen with Khosla's[2] concept of design that it does not take into account the drastic change in uplift pressure distribution below the floor due to heterogeneity and anisotropy. The uplift pressure is not found to be sensitive to the length of the floor in anisotropic soils as the head loss is primarily in the vertical direction. The only consideration visualized by Khosla was to give a generous factor of safety to the critical value of the exit gradient to take care of heterogeneity and anisotropy without anticipating the drastic increase in the uplift pressure in the downstream portion of the floor due to heterogeneity.

In this study finite element analysis, for subsurface flow below a barrage has been carried out to obtain an insight into the effects of heterogeneous and anisotropic soils on the uplift pressures and exit gradients. The study reveals that the isotropic and anisotropic soils behave differently under subsurface flow considerations and anisotropy must be considered in the design of a barrage. Also, contrary to normal design practice of not giving importance to a pervious layer, the present study shows that a pervious layer below the foundation of a hydraulic structure may affect the design more severely compared to an impervious layer. The results are summarized below:

(1) If the middle layer (say silt, permeability 0.00001 cm/sec) is around 1000–10,000 times less pervious compared to the upper layer (say sand, permeability 0.01 cm/sec), then it behaves as impervious irrespective of its thickness for both the isotropic and anisotropic soils. If the middle layer (sand) is around 1000–10,000 times more pervious compared to upper layer (silt), then it behaves as pervious irrespective of its thickness for both the isotropic and anisotropic soils. For these values, the effect of the layer below the middle layer can be neglected irrespective of its permeability.

(2) The location of impervious layer below the sheet piles does not affect the uplift pressures significantly for both the isotropic and anisotropic soils. The exit gradients (2.75–1.72 for example) reduce as the distance of the impervious layer below the pile is reduced.

(3) In contrast to impervious layer, the location of pervious layer below the sheet piles has a significant impact on uplift pressures and exit gradients for both the isotropic and anisotropic soils. It increases the exit gradients drastically (2.75–5.71, for example). It drastically changes the uplift pressures for isotropic soils, while only marginally affects the uplift pressures for anisotropic soils. Therefore, the location of pervious layer below the sheet pile will have a major impact on the design of a barrage on permeable foundations.

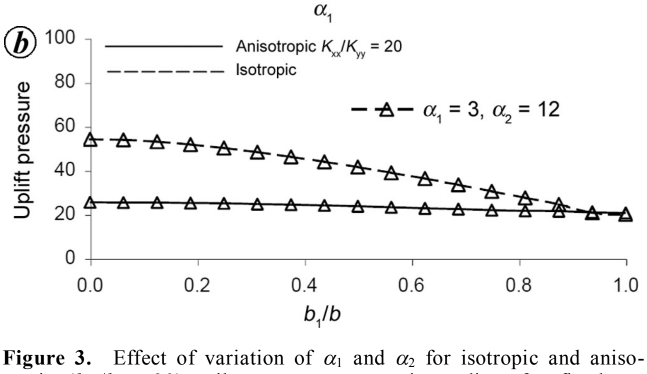

Figure 3. Effect of variation of α_1 and α_2 for isotropic and anisotropic ($k_{xx}/k_{yy} = 20$) soils. ***a***, α_1 versus exit gradient for fixed α_2; ***b***, Uplift pressure versus distance for unequal piles ($\alpha_1 = 3$ and $\alpha_2 = 12$).

(4) The exit gradients hardly reduce with increase in the depth of upstream sheet pile for isotropic soils (4.67–4.02, for example), but significantly reduce for anisotropic soils (7.13–3.75, for example) along with an additional advantage of the reduction of the uplift pressures on the entire floor. Therefore, the depth of upstream sheet pile can be an important factor for the economical design of a barrage on anisotropic soils.

Although the safety of the structure is ensured by assuming high factor of safety based on Khosla's concept[2] of barrage design, the present study indicates that it may still not lead to a safe design for anisotropic soils. Based on the above analysis, there is also a necessity to revise IS code[15] as the current scope mentions that 'This standard lays down guidelines for hydraulic design of barrages and weirs in alluvial foundations'. IS code[15] does not mention anything about the type of subsurface strata and therefore, the scope should be revised to categorically mention that this standard is applicable only for isotropic and homogeneous soils with no intermediate layers of different soils or without any stratifications.

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