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Design method for horizontal drains in liquefiable soil

D. De Sarno, G. Fasano, E. Bilotta & A. Flora
University of Naples Federico II, Naples, Italy

ABSTRACT: The paper describes a fast design method for horizontal drains to be used as a mitigation technique for liquefaction, developed in the framework of the European project LIQUEFACT. During the earthquake, this ground improvement technique allows to reduce the pore pressure build up under existing buildings, where more conventional vertical drains cannot be used (being it difficult to install them). By reducing the pore pressure increments, the horizontal drains can reduce the liquefaction risk for shallow foundations. The problem is modelled with a bidimensional geometry, applying the consolidation equation in the hypothesis of Terzaghi-Rendulic and solving it with a finite difference method. The solution is calculated for different geometrical layouts and removing the simplified hypothesis (used to design vertical drains) of an indefinite symmetry; moreover, it takes into account the influence of a vertical water flow when drainage is allowed at the ground level. The pore pressure build-up is introduced in a simplified manner with an accumulation term suggested in literature. A parametric analysis has been performed and is reported in the paper to obtain design charts. They may be used to define the spacing between drains once the geometric layout, the ground conditions and the seismic input are defined.

1 INTRODUCTION

Soil liquefaction is a critical phenomenon triggered by the pore water pressure build-up due to dynamic actions during earthquake in loose cohesionless soils below the ground water table. This leads to a reduction of effective stresses, along with a decrease of shear stiffness and strength, that may possibly nullify. Liquefaction phenomena have caused significant economic losses around the world (Bray et al. 2014).

In the last few years, scientific research has especially focused on validation of mitigation techniques with the aim to reduce damages on structures and infrastructures on sites characterized by high liquefaction risk (Mitchell 2008, Sarker & Abedin 2015). Among others, drainage systems are one of the most efficient techniques for liquefaction mitigation; drains act as seepage surfaces reducing drainage distance thus decreasing excess pore water pressure.

Drainage systems are usually composed of vertical drains, constituted of gravel columns or tapes. However, they can be hardly placed below existing structures. In this case, horizontal drains can represent a suitable solution, which can be placed below existing structures thanks to directional drilling technology (Allouche et al. 2000), which allows to perform bores in built environment. They are made of microperforated cylindrical tubes with at least one end accessing to atmosphere (to ensure hydrostatic condition); maximum diameter is limited by technology to about 0.3 m. However, differently from vertical drains, no design approach is available for the application of this technique in dynamic conditions. The solutions for vertical drains proposed by Seed & Booker (1976), and revised by Bouckovalas et al. (2009), are developed for indefinite distribution, thus axial-symmetric condition can be considered; conversely, horizontal drains are limited to 2 or 3 rows and they cannot be represented by the same geometrical layout generally adopted in the available solutions for vertical drains. In this work, the approach of Seed & Booker (1976) was extended to horizontal drains.

2 NUMERICAL SOLUTION

The development of excess pore water pressure during earthquake is due to volumetric-distortional coupling in saturated loose cohesionless soils; thus, it is rigorously a complex coupled hydro-mechanical problem. However, this process can be studied with an uncoupled approach, by introducing a build-up function for excess pore water pressure. Once the accumulation term is added, the consolidation equation can be solved. In bi-dimensional conditions and in the hypothesis of Terzaghi-Rendulic (Rendulic 1936), it can be written as:

$$\frac{k}{\gamma_w}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=m_v\left(\frac{\partial u}{\partial t}-\frac{\partial u_g}{\partial N}\frac{\partial N}{\partial t}\right) \tag{1}$$

where k is the permeability coefficient, u is the excess pore water pressure, m_v is the bulk compressibility modulus, N is the number of cycles and u_g is the induced excess pore water pressure, whose build-up is represented by the last term of equation 1. The equations 2a and 2b, proposed by Bouckovalas et al. (2009), define the evolution of pore water pressure build-up with number of cycles:

$$\frac{\partial \mathrm{u_g}}{\partial \mathrm{N}}=\frac{\sigma'_0}{\pi \mathrm{AN_l}}\frac{1}{\left(\frac{\mathrm{t}}{\mathrm{t_d}}\frac{\mathrm{N_{eq}}}{\mathrm{N_l}}\right)^{1-\frac{1}{2\mathrm{A}}}\cos\left(\frac{\pi}{2}\mathrm{r_u}\right)};\quad \frac{\partial \mathrm{N}}{\partial \mathrm{t}}=\frac{N_{eq}}{t_d}; \tag{2a, 2b}$$

where σ'_0 is the vertical effective stress, N_l is the number of cycles that leads to liquefaction (Kramer & Wang 2015), N_{eq} is the earthquake equivalent number of cycles (Green & Terri 2005, Seed & Idriss 1971), r_u is the ratio between the excess pore water pressure and the vertical effective stress, t_d is the earthquake significant duration (Trifunac & Brady 1975) and A is a parameter that affect the shape of build-up curve (Seed et al. 1975). It is worth noting that the build-up term is a non-linear function of r_u. From equations 1 and 2:

$$T_{ad}\left(\frac{\partial^2 r_u}{\partial\left(\frac{\mathrm{x}}{\mathrm{d}}\right)^2}+\frac{\partial^2 \mathrm{r_u}}{\partial\left(\frac{\mathrm{y}}{\mathrm{d}}\right)^2}\right)=\frac{\partial \mathrm{r_u}}{\partial\left(\frac{\mathrm{t}}{\mathrm{t_d}}\right)}-\frac{N_{eq}}{\pi \mathrm{AN_l}}\frac{1}{\left(\frac{\mathrm{t}}{\mathrm{t_d}}\frac{N_{eq}}{\mathrm{N_l}}\right)^{1-\frac{1}{2\mathrm{A}}}\cos\left(\frac{\pi}{2}\mathrm{r_u}\right)} \tag{3}$$

where the time factor, T_{ad}, is a function of earthquake properties and hydro-mechanical characteristic of the soil:

$$T_{ad}=\frac{t_d k}{d^2 m_v \gamma_w} \tag{4}$$

Dimensionless space and time variables, obtained by dividing the corresponding dimensional variables by drains diameter and significant duration respectively, were adopted to solve the consolidation problem. The geometric layout analysed in this study is presented in Figure 1; a drainage system made of three rows of drains in a staggered disposition (α=60°) is assumed. The shallowest row is located at depth H' from the ground surface. Two symmetrical vertical planes (as shown in Figure 1) constitute the vertical impervious boundaries of the domain, except for three segments representing the drains characterized by zero excess pore pressure condition. The lower boundary was modelled as impervious at a distance equal to 2s/d from the last row of drains, thus minimizing the effect within the domain of interest. Indeed, the solution is given in a smaller volume in which the effect of drainage is significant, whose extent is up to 0.5 s/d underneath the last row of drains.

The upper boundary hydraulic condition can be either pervious or not. In fact, earthquake can induce liquefaction at depth up to about 20 m, thus it is also possible that a less permeable layer (made of silt or clay) can overly liquefiable one. This affects the hydraulic boundary

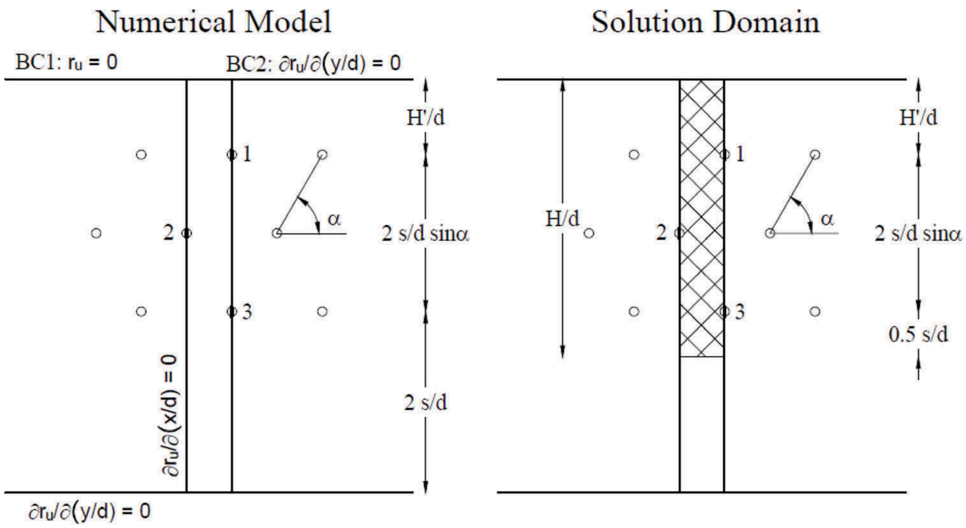

Figure 1. Numerical and solution domains of the geometrical system made of three rows of drains in a staggered disposition.

condition and, consequently, the pore pressure build-up in the shallowest part of liquefiable soil. The importance of the upper part of soil profile is related to the presence of structures above, which may suffer larger vertical displacements, and subsequent damages, in case of an excessive pore water pressure build-up. Therefore, two limit conditions were considered for the upper boundary, a pervious boundary (BC1) and an impervious one (BC2), which bound all the intermediate cases.

The geometric layout is a function of both s/d and H'/d; the problem was solved with a finite difference method. Parametric analyses by varying the geometry (s/d, H'/d), soil and earthquake properties (T_{ad}, N_{eq}/N_l) were carried out.

3 NUMERICAL RESULTS

The numerical solution of the problem provides the $r_u(x/d,\ y/d,\ t/t_d)$ time history in each point of the domain, based on s/d, H'/d, T_{ad} and N_{eq}/N_l. In Figure 2, the vertical profiles of the mean, $r_{u,mean}(y/d,\ t/t_d)$ and maximum, $r_{u,max}(y/d,\ t/t_d)$, values of r_u on the horizontal plane (at the end of earthquake significant duration, $t/t_d=1$) are presented. Results refer to H'/d=10, $N_{eq}/N_l=1$ and $T_{ad}=50$, with varying spacing and upper boundary condition. At increasing spacing, the excess pore water pressure increases as well in each point of the domain, regardless of upper boundary condition, along with an expansion of the thickness influenced by drains. Maximum and mean excess pore water pressure slightly differ only at drain depths.

The effect of the upper boundary condition is significant especially above the first row of drains, as it can be observed in Figure 2 where both solutions are presented. An impervious boundary (BC2) leads to higher pore water pressures in the upper part of the domain compared to pervious boundary case (BC1). However, the difference becomes negligible with depth; in the comparison proposed in Figure 2, the difference extinguishes below the second row of drains.

By following the same approach proposed for vertical drains by Bouckovalas et al. (2009), charts to design horizontal drains in liquefiable soils were obtained. The time history of maximum, $r_{u,max}(t/t_d)$, and mean, $r_{u,max}(t/t_d)$, values of r_u in the whole solution domain (Figure 1) were calculated and their maximum values were determined; indeed, due to seepage induced by drains, the worst condition is not necessarily gained at the end of earthquake. The charts provide $r_{u,max}$ and $r_{u,mean}$ at varying spacing and T_{ad}; each chart refers to a specific H'/d and N_{eq}/N_l (Figure 3).

At increasing T_{ad}, regardless of top boundary condition, the dissipating capacity of the system (at equal spacing) significantly enhances and lower r_u are obtained in all the range of spacings; as expected, at increasing s/d and equal T_{ad}, the efficiency of system decreases.

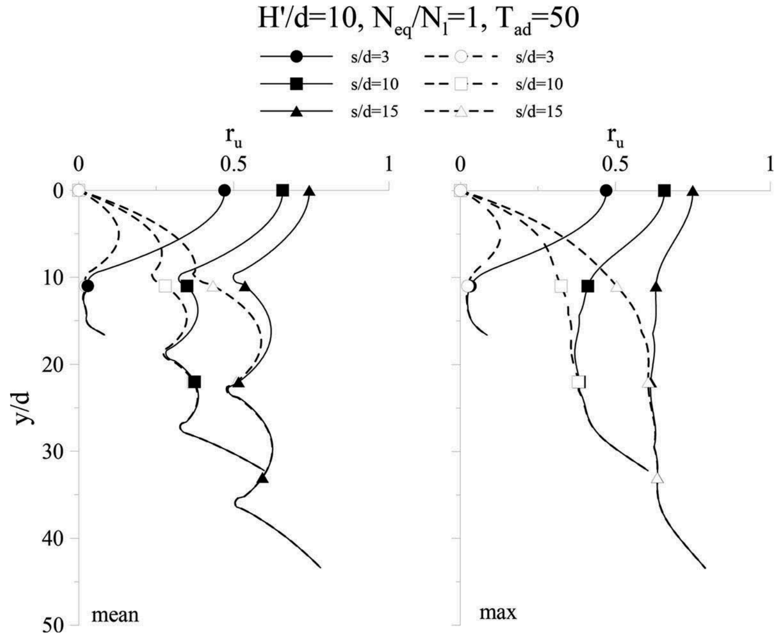

Figure 2. Vertical profiles of $r_{u,mean}$ (left) and $r_{u,max}$ (right) for H'/d=10, T_{ad}=50 and N_{eq}/N_l=1 (dashed and solid lines refer to BC1 and BC2, respectively).

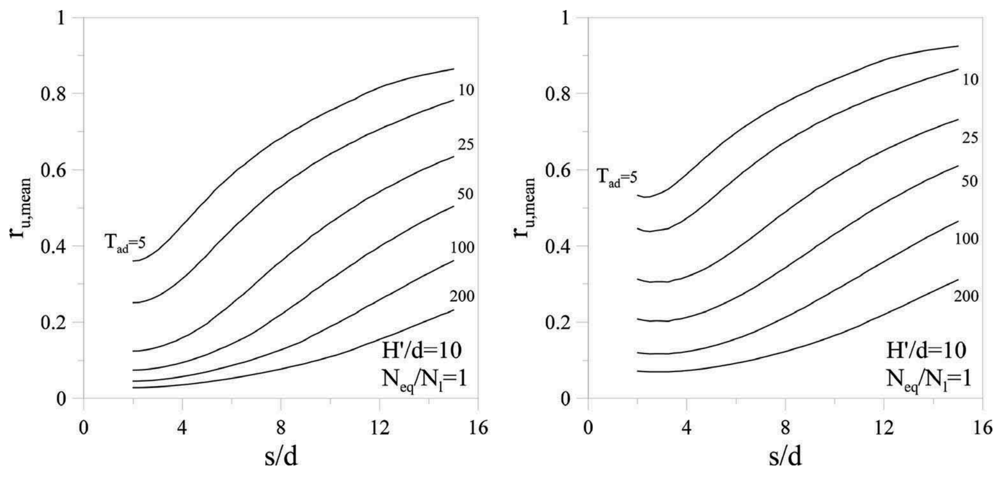

Figure 3. Design charts for three rows of horizontal drains and two boundary conditions: BC1 (left); BC2 (right).

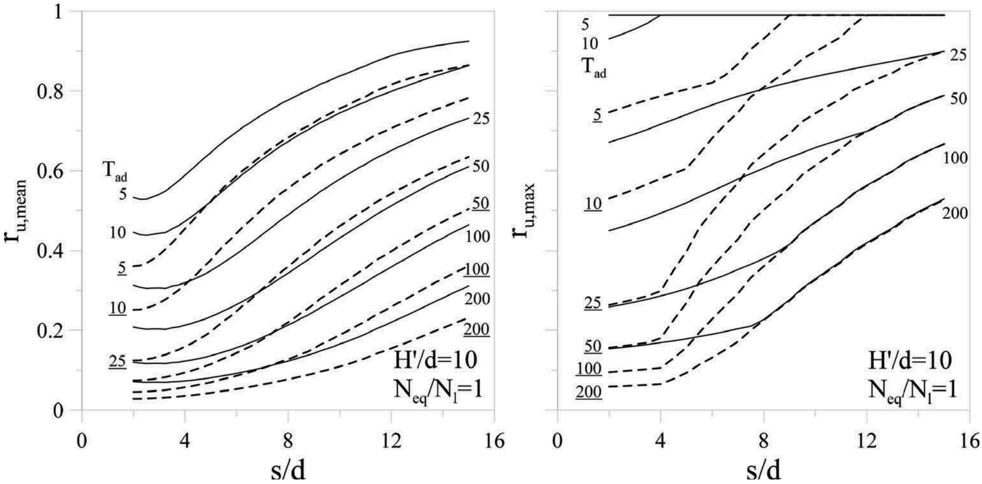

Figure 4. Comparison between design charts for three rows of horizontal drains with BC1 condition (dashed lines) and BC2 condition (solid lines).

3.1 *Solutions comparison*

The effect of upper boundary condition shown in Figure 2 can also be noticed in design charts; in Figure 4, a comparison between solutions for both maximum and mean excess pore water pressure ratio at varying T_{ad} and s/d is shown. The curves referring to pervious boundary condition (BC1, dashed lines) are always below the curves (corresponding to the same T_{ad}) with impervious boundary conditions (BC2, solid lines) due to the absence of the top seepage surface. This effect is enhanced at low spacings and time factors (T_{ad}). The difference in terms of $r_{u,max}$ between the two boundary conditions goes to zero at increasing s/d. The same trend cannot be observed on $r_{u,mean}$; indeed, at increasing s/d, the maximum value tends to be attained below drains, far from the influence of upper boundary condition, so that it only affects the mean value of r_u.

The design of horizontal drains in dynamic condition for mitigation of liquefaction risk is generally carried out in the hypothesis of radial consolidation, so that the solution proposed for vertical drains by Seed and Booker (1976) and revised by Bouckovalas et al. (2009) can be applied. They solved an axial-symmetrical flow problem in the hypothesis of indefinite vertical drains system with regular grid. By using these solutions, the contribution of vertical drainage induced by top pervious surface is neglected. Moreover, the hypotheses of radial flow and indefinite drainage system can be far from the case of horizontal drains even if top surface is impervious; indeed, as already pointed out, there can hardly be more than 3 rows of drains. Thus, a comparison between axial-symmetrical solutions after Bouckovalas et al. (2009) and bi-dimensional solution, in the case of impervious upper boundary condition, was carried out.

Figure 5 shows the comparison between Bouckovalas solution (dashed lines) and bidimensional solution (solid lines) for H'/d equal to 5 and 10. Solutions substantially differ in all the range of T_{ad} values and spacings, for both maximum and mean r_u. Design charts for vertical drains, despite the impervious upper surface, appear to be not trustworthy for horizontal drainage system.

3.2 *Design method*

At varying H'/d and N_{eq}/N_l it is possible to provide design charts. To use the charts, it is necessary to know the bidimensional consolidation coefficient, the strength of soil to

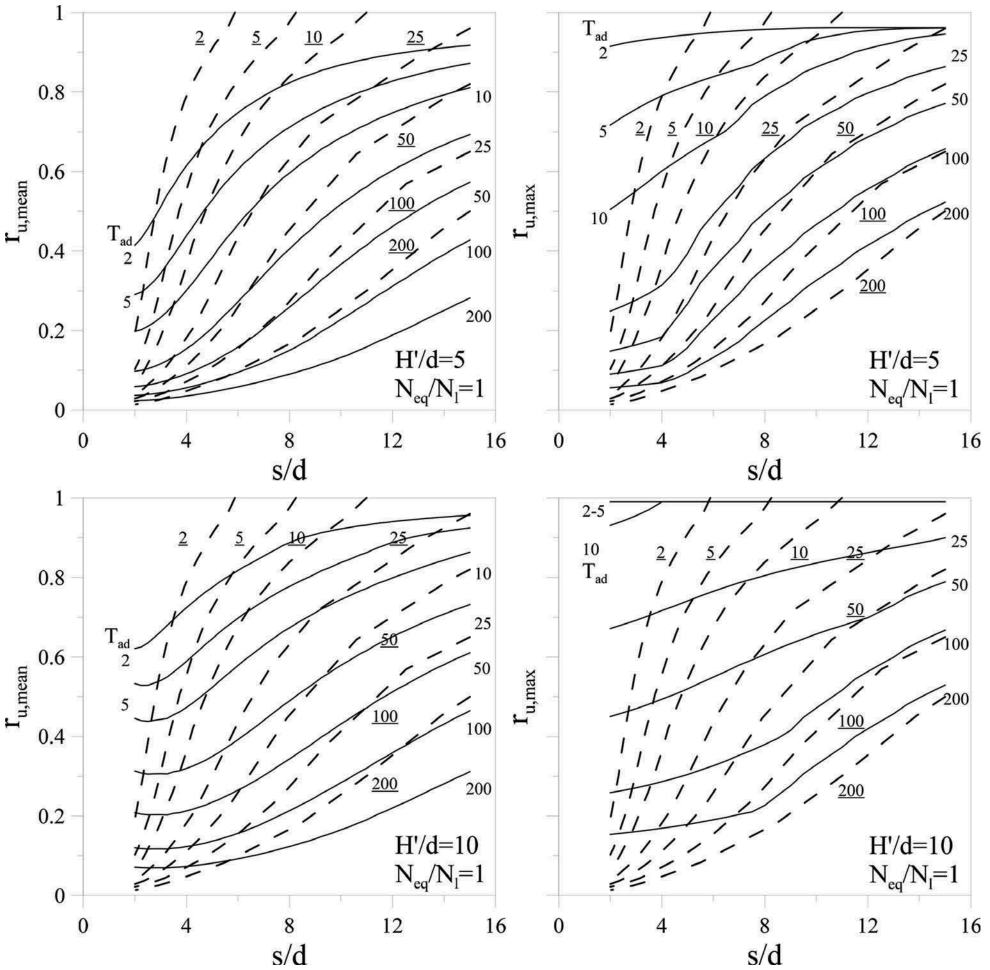

Figure 5. Comparison between design charts of Bouckovalas et al. 2009 (dashed lines) and model, made of three rows of horizontal drains, with hypothesis BC2 (solid line).

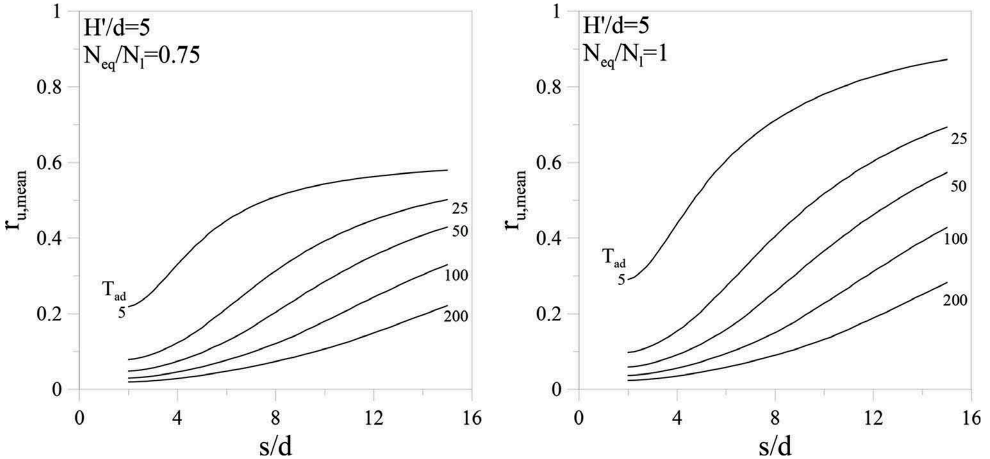

Figure 6. Design charts for H'/d = 5 with N_{eq}/N_l=0.75 (left) and N_{eq}/N_l=1 (right).

liquefaction (N_l) and site seismic characteristics (N_{eq}, t_d). Then, once the drain diameter and the first drain row depth are set (d, H'), chart is uniquely determined, along with the curve to be used. Based on design requirements, it is possible to determine the desired value of excess pore pressure ratio $r_{u,mean,d}$ (or $r_{u,max,d}$) and the corresponding spacing can be chosen.

In some cases, even if pore water pressure ratio is lower than 1 and liquefaction does not occur, pore water pressure can be high enough to reduce significantly shear stiffness of soil, thus leading to non-negligible settlements. To reduce pore water pressure build-up, horizontal drains could be used even if N_{eq}/N_l is lower than 1 (which implies that the expected seismic action is not able to cause liquefaction); thus, analyses with N_{eq}/N_l = 0.75 were also carried out, as shown in Figure 6, where maximum excess pore water pressure ratio is always lower than 1. A considerable effect of drainage system can be observed also in this case.

4 CONCLUSIONS

The paper describes the solution of the consolidation equation in the hypothesis of Terzaghi-Rendulic to design the spacing of horizontal drains to be used as a mitigation technique against soil liquefaction.

The pore pressure build-up is introduced in a simplified manner with an accumulation term suggested in literature. The solution is calculated with a finite difference method for different geometrical layouts and removing a few simplifying hypotheses, that are generally adopted for vertical drains. The study shows that design charts generally used for vertical drains cannot be used trustfully for horizontal drainage systems. Hence new design charts have been produced for the latter case based on the described solution.

These charts may be used to define the spacing between drains once the geometric layout, the ground conditions and the seismic input are defined.

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