On Numerical Simulation of Vertical Drains Using Linear 1-Dimensional Drain Elements

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Mojtaba E. Kan, Buddhima Indraratna, and Cholachat Rujikiatkamjorn

Abstract

This Technical Note addresses an issue of vertical drains simulation using linear drain elements for radial consolidation. A new method is proposed which enables the application of linear drain elements while maintaining acceptable accuracy. The robustness of the proposed method is examined satisfactorily through the simulation of a unit cell representing a single drain and the application of multi-drain condition for the Ballina Embankment considering both elastic and elasto-plastic soil domains.

The proposed model shows that the settlement and excess pore pressure predictions are almost the same as those determined for the ideal. The effectiveness of this method is also demonstrated through the reduction of the numerical convergence time for both unit cell and multi-drain conditions.

Keywords: Vertical drains, Consolidation, Drain, Drain elements, Smear Zone, Numerical simulation

1 Introduction

The behaviour of soft clay stabilized with prefabricated vertical drains (PVDs) has remained difficult to predict accurately, although many numerical modelling tools have become available. The classical radial consolidation theory using a unit cell was well documented in Barron (1948) and later was extended by Hansbo (1981). The unit cell analysis however fails to predict the settlement and lateral displacement far from the embankment centreline where the assumption of zero lateral displacements is not valid anymore. To analyse a multi-drain system, most finite element analyses on embankments are usually conducted based on the plane strain assumption given the significantly longer dimension of the embankment compared to its width, although the consolidation around a vertical drain is axisymmetric (3D). In large projects, there are thousands of PVDs, and a comprehensive 3D analysis to capture all these individual unit cells is cumbersome and often impractical. The multidrain analysis, therefore, is essential to incorporate the effect of variations in lateral confinement along the embankment width. Following the initial developments in this field (e.g. Cheung et al., 1991, Hird et al., 1992, Chai and Carter 2011, Chai et al. 2013), Indraratna and Redana (1997, 2000) extended the conversion technique to include the effects of smear zone, a zone of soil around the drain with lower permeability due to the installation of the vertical drain. By employing a realistic equivalent plane strain analysis for PVDs, the need for cumbersome 3D axisymmetric analysis for each drain can be avoided as further explained by Rujikiatkamjorn et al. (2008).

Although a significant amount of research works have been devoted to model smear zone, there are limited studies about employing various forms of drain elements in numerical simulation of multidrain systems (e.g. in Zhu and Yin, 2000, Indraratna et al., 2003, Ngo et al. 2020). Nowadays, however, few numerical simulation packages such as PLAXIS (Brinkgreve et al., 2015) have one-dimensional (1D) drain element using a zero-thickness line. In FLAC (Itasca Consulting Group Inc., 2008), the drain shall be simulated using assigned pore water pressure on particular nodes along the drain and therefore the width of the drain cannot be simulated directly in simulations (e.g. in Chai et al. 2013; Parsa-Pajouh et al., 2014; Nguyen et al. 2018).

In this Note, a novel approach is introduced by which the drain elements can be appropriately used in the simulation of PVDs and their surrounding smear zone. In this approach, the effect of drain size in numerical modelling is incorporated by specifying an adjusted size of the smear zone based on given drain size and soil permeability.

2 Proposed simulation scheme

Analytical modelling of radial consolidation involves a cylinder of soil around a single vertical drain (Figure 1a). Figure 1(b) shows a unit cell with an effective diameter of d_e, surrounding a single drain with diameter of d_w and smear zone with a diameter of d_s. The horizontal permeability coefficients of the undisturbed and smear zone are denoted as k_h and k_s, respectively. Under a plane strain analysis (Figure 1c), the equivalent horizontal permeability can be calculated using the conversion technique described by Indraratna and Redana (2000):

$$\frac{k_{hp}}{k_h} = \frac{2/3}{\ln(n) - 0.75} \qquad (1)$$

where $n = d_e / d_w$. The converted coefficients of permeability in plane strain model for undisturbed and smear zone are k_{hp} and k_{sp}, respectively. The equivalent permeability of the smear zone under plane strain condition can be calculated from:

$$\frac{k_{sp}}{k_{hp}} = \frac{\beta}{\frac{k_{hp}}{k_h}\left[\ln(n) + \frac{k_h}{k_s}\ln(s) - 0.75\right] - \alpha} \tag{2}$$

where $s = d_s / d_w$, α and β can be calculated from:

$$\alpha = \frac{2}{3}\frac{(n-s)^3}{n^2(n-1)}\ ,\ \beta = \frac{2(s-1)}{n^2(n-1)}\left[n(n-s-1) + \frac{1}{3}(s^2+s+1)\right] \tag{3}$$

A plane strain unit cell shown in Figure 1 can be conveniently simulated using linear 1D drain elements. To correctly simulate the drain with its thickness (Figure 2a), the drain should be represented by 2D elements sandwiched by 1D drain elements on both sides (Case I). In this approach, owing to the relatively small thickness of the drain compared with the surrounding soil, an extremely small mesh size inside the drain is required.

To avoid the above situation, one may decide to simulate the drain with a single drain element (Case II), shown in Figure 2(b). In this case, however, the actual size of the drain is ignored and therefore the size of the smear zone is larger than those measured in the field (Indraratna et al., 2014) or laboratory conditions (e.g. Rujikiatkamjorn et al., 2013).

One possible approach to solve this problem is to introduce the smear zone with a permeability of k', and width of $2b'$ (Case III), (Figure 2c) by taking into account the vertical drain's equivalent thickness.

If flow continuity is satisfied, an equivalent permeability of the undisturbed-smeared soil systems in each case can be described below.

For Case I (Figure 2a):

$$\frac{B}{\bar{k}} = \frac{b_w}{k_w} + \frac{b_s - b_w}{k_{sp}} + \frac{B - b_s}{k_{hp}} \tag{4}$$

For Case II (Figure 2b):

$$\frac{B}{\overline{k}} = \frac{b'}{k'} + \frac{B - b'}{k_{hp}} \tag{5}$$

where $\overline{k}$ is the average equivalent permeability of the unit cell. As the permeability of the vertical drain is very high (Indraratna and Chu, 2005), the term b_w / k_w is much smaller than two other terms and then equation (4) can be re-written as:

$$\frac{B}{\overline{k}} = \frac{b_s - b_w}{k_{sp}} + \frac{B - b_s}{k_{hp}} \tag{6}$$

The right-hand side of Equations (5) and (6) should be equal, which yields:

$$b' = b_s \frac{k_{hp} - k_{sp}}{k_{hp} - k'} - \frac{b_w k_{hp}}{k_{sp}\left(k_{hp} - k'\right)} \tag{7}$$

The permeability of the converted smear zone however can be assumed the same as the original smear zone, i.e. $k' = k_{sp}$, therefore, Equation (7) can be simplified to have:

$$b' = b_s - \frac{b_w}{1 - k_{sp} / k_{hp}} \tag{8}$$

By defining $s' = b' / b_w$, Equation (8) can be written as:

$$s' = s - \frac{1}{1 - k_{sp} / k_{hp}} \tag{9}$$

Similar to the plane-strain condition, it can be shown that the same adjusted size of the smear zone is required to use (1D) drain elements in the simulation of an axisymmetric unit cell. The corresponding diameter of the adjusted smear zone for axisymmetric condition, d', and the smear size ratio, $s' = d'/d_w$, can be calculated using the following equations:

$$d' = d_s - \frac{d_w}{1 - k_s/k_h} \text{ and } s' = s - \frac{1}{1 - k_s/k_h} \quad (10)$$

Parsa-Pajouh et al. (2014) showed that the value of s may vary from 1.6 to 7 times and the range of the undisturbed to smeared permeability ratios (k_s / k_h) might be 0.1–0.8. The variation of s' with s for a range of possible k_s / k_h values and based on Equation (10) is shown in Figure 3.

3 Verification of the Approach

Indraratna et al. (2005) reported the results of analytical and numerical modelling to predict the consolidation behaviour of soft estuarine Sydney clay using a physical model. Similar to their study, a 0.95 m high, 0.45m diameter unit cell was simulated with the drain and surrounding smear zone diameter of 50 and 170 mm, respectively. The triangular elements (six-node quadratic displacement and linear pore pressure) were used in the finite element discretization throughout the Note (Figure 4a). The drain was simulated using a linear drain element. Simulations were performed using PLAXIS 2D (Brinkgreve et al., 2015) were divided into three cases:

- Case I: vertical drain was simulated using ultra-fine mesh in axisymmetric condition (Figure 4b). A total of 1095 elements were used to model only half of the problem due to the symmetric conditions.
- Case II: vertical drain was simulated using 1D drain elements (Figure 4c) with a total of 1716 elements.

- Case III: vertical drain was simulated using 1D drain elements, with a converted size of the smear zone based on the size of the drain and normalized permeability of the smear zone, (Figure 4d). A total of 1540 elements were used in this case.

The soil behaviour was assumed to be linear elastic with m_v=0.001 m^2/kN and the zero lateral displacements were imposed (Poisson's ratio = 0) for the unit cell. The horizontal undisturbed soil permeability (k_h) was taken as 10^{-10} m/ s, and the ratio of the undisturbed permeability to the smear zone permeability (k_h / k_s) was assumed to be 3.0 (Indraratna and Redana, 2000). Conversion of the permeability values for plane-strain simulations in Cases (II) and (III) was performed using Equations (1) and (2). In Case (III) the size of the smear zone was adjusted using Equation (8). The converted size of the smear zone after application of the proposed scheme was 106 mm which compared with the original size of 170 mm shows a 37% reduction in size. A summary of the required conversion calculations is given in Table 1. By the size of the smear zone in Case (III), it is expected that the effect of drain size would be incorporated.

In all cases, the top, bottom, and outer boundaries were set as impermeable to allow only horizontal flow. After establishing the at-rest in-situ stresses, the drain elements were activated and then a surcharge load of 50 kPa was applied on top of the cell. To capture the equal-strain condition, rigid elements were used at the top of the soil surface where only vertical displacement was allowed to prevent any rotation. The fully implicit time-marching scheme with a default error tolerance of 1% was adopted to ensure adequate and swift convergence throughout the Note.

The normalized excess pore water pressure in the numerical simulations was calculated using the average values at observation points. The presented analytical solution is based on the radial consolidation equation by Hansbo, (1981) where the coefficient of consolidation in a radial direction, equal to 0.315 m^2/year. It can be seen in Figure 5(a) that the results of the numerical simulations in Case I are very close to those of the analytical solution, as expected. While the simulated curve for excess pore pressure in Case II deviates from the analytical results especially after 10 days, the proposed scheme in Case III shows similar results compared with the analytical model. The effect of different numerical schemes can be clearly shown using the percentage error in the calculation of the excess pore water pressure (Figure 5b). It can be seen that in Case II the error in the calculation of excess pore water pressure can be as high as 8% at 150 days, while by application of the proposed method (Case III) the error decreases to be less than 4%. Note that the application of the numerical model may introduce an inherent error that is depicted in the simulation of Case I and might be as high as 2%. If the inherent error is subtracted from the numerical simulation results, the net maximum error in the proposed model is less than 2% which is acceptable for most practical applications.

4 Application to a case study under multidrain simulation

In the unit cell, simulation of the radial consolidation using Case 1 seems to be the most accurate numerical scheme among the 3 proposed schemes. In multidrain problems however, it might be very time-consuming to use a simulation scheme based on Case I due to the excessive number of small size elements to simulate the drain. In contrast, the application of the proposed simulation scheme based on Case III would provide enough accuracy very close to the ideal condition and without the need for time-consuming simulation.

To demonstrate the performance of each scheme, two multidrain problems were analysed, one based on elastic behaviour attributed to Sydney soft clay, and the other one based on an elastoplastic condition corresponding to the plastic Ballina clay.

4.1 Multidrain system in elastic condition

For relatively small embankment, a multidrain system consisting of 5 PVDs, 10 m deep with 1 m spacing, was considered with the same properties of Sydney soft clay described in the previous section.

Simulations were performed in two cases:

- Case A: PVDs were simulated similar to Case I under plane strain condition (Figure 6a), with a total of 9606 soil elements
- Case B: PVDs were simulated similar to Case III with the converted size of the smear zone (Figure 6b) with a total of 5804 soil elements.

Conversion of the permeability under plane strain condition is performed using equations (1) and (2). In Case B the size of the smear zone is adjusted using the proposed scheme which resulted in a 22% reduction of smear zone width. All required parameters based on each conversion scheme are summarized in Table 1.

The in-situ stresses were established in the model using $k_o = 1$ and then the drains were activated after 5 days. A surcharge load of 50 kPa was applied then on top of the model in a width of 5 m from the centreline.

Figure 7 shows the rate of consolidation calculated based on the ratio of time-dependent settlement at point A (see Figure 6). It can be seen that both cases show the same rate of consolidation at the centreline. It can be seen that for both points B and C (see Figure 6), Case B provides the excess pore water pressure predictions almost identical to those of Case A.

4.2 Multidrain system in elastoplastic condition using soft soil model

A trial embankment was constructed at the southern approach of the upgraded highway to Emigrant Creek, north of Ballina town NSW, Australia, to study the effectiveness of different ground improvement techniques. A section of this embankment, namely Section-A, was selected, in which the circular-shaped PVDs with surcharge only was used for ground stabilization (Kelly and Wong, 2009). In this section of the embankment, the soft clay layer was 7 m in depth, underlain by stiff Pleistocene silty clay which is assumed unaffected during the ground improvement. The PVDs were 34 mm in diameter, installed at a spacing of 1.0 m in a square pattern (Indraratna et al., 2012). The embankment height was raised to 5.4 m in multiple stages in 1200 days, using fill materials with an average unit weight of 20 kN/m^3 (Parsa-Pajouh et al., 2014).

Only half of the embankment is shown here owing to the symmetric geometry of the system (Figure 8a). Two cases were considered for simulations:

- Case C: An ideal model with two drain elements per each PVD and ultra-fine mesh inside the drain (Figure 8b), with a total number of 13800 soil elements
- Case D: The proposed model with the converted size of the smear zone (Figure 8c) with a total number of 4143 soil elements.

As summarized in Table 1, the permeability for the plane strain condition was calculated using Equations (1) and (2). The size of the smear zone was adjusted in Case D, using the proposed scheme and consequently, the width of the smear zone was reduced by 12%.

The required material parameters for Soft Soil model were adopted from relevant literature, mainly from Indraratna et al. (2012), as listed in Table 2. The staged construction (Figure 9) was simulated as follows (a) at-rest equilibrium condition, (b) the placement of working platform (0.6 m high),

(c) rest period for installation of PVDs, (d) placement of sand blanket (0.7 m thick), (e) rest period for installation of instruments, and (f) raising the embankment to the ultimate height (7m). In each stage, the corresponding surcharge load was applied on top of the model and the lateral batter of the embankment was simply simulated using a trapezoidal load distribution (Figure 8a).

Figure 9 shows the results of simulations compared with the measured surface settlement at SP1, at the embankment centreline. It can be seen that both cases show the same rate of settlement at the centreline which is fairly close to the field measurements. The proposed model in Case D, therefore, shows the settlement predictions almost the same as those of Case C with the ideal condition but highly intense mesh. Although the validation using physical model and case studies was conducted, further validation from more studies can enhance clarity and confidence in using this approach.

4.3 Effectiveness in saving the CPU time

The benefits of the proposed scheme however can be further highlighted if the number of elements and the time of CPU for simulation are taken into account.

For the problem of the multidrain system in Sydney clay with a drain width of 50 mm, it was shown that the application of the proposed model reduced the number of elements by 40%, from 9606 elements in the ideal case (Case A) to 5804 in proposed case (Case B). In the problem of Ballina Bypass embankment with smaller 34 mm diameter drains, the number of elements reduced from 13800 in the ideal case (Case C) to 4143 in the proposed case (Case D), which shows a significant 70% reduction in the number of elements. This comparison shows that as the size of the drain in the prototype problem decreases, more intense mesh is necessary to simulate the model in Case I, and therefore the benefits of the proposed scheme (Case III) to reduce the number of elements and consequently the CPU time are more pronounced.

From the perspective of the calculation time, the effect of constitutive model complexity should also be taken into account. The required processor times for simulation of the two multidrain systems are compared in Figure 10, where on the horizontal axis, the term Elastic denotes the Sydney clay problem, and the term Elastoplastic is used to show the Ballina Bypass problem. The CPU times are normalized for the ideal conditions in each problem and the simulations were performed using a PC with 3.6 GHz Intel Xenon CPU and 32 GB RAM. It can be seen that using the proposed scheme reduced the CPU time by 50-70%.

5 Conclusions

An alternative simulation scheme was proposed where the effect of the drain size could be converted to an equivalent reduction in the size of the smear zone of the soil surrounding the drain. The robustness of the proposed method was demonstrated using both single drain and multi-drain systems, in comparison to an ideal or perfect drain simulation. It was shown that in both single and multi-drain systems, the proposed method can predict the behaviour of the soil-drain system accurately with insignificant deviation from the ideal simulation. It was shown that the efficiency of the simulation can be significantly improved by the application of the proposed method, and CPU time saving of 50-70% was observed in two multi-drain problems discussed within the scope of this Note.

6 Acknowledgment

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7 Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

8 References

Barron, R. A. 1948. Consolidation of fine-grained soils by drain wells. *Transactions of American Society of Civil Engineers, Paper No. 2346,* 113**,** 718–742.

Brinkgreve, R., Kumarswamy, S. and Swolfs, W. (eds.) 2015. *PLAXIS 2D 2015, User's Manual,* Netherlands: Plaxis bv.

Chai, J.C. and Carter, J.P. 2011. Deformation Analysis in Soft Ground Improvement, Springer, Berlin.

Chai, J.C., Bergado, D.T, Shen, S.L. 2013 Modelling prefabricated vertical drain improved ground in plane strain analysis. Ground Improv., 166 (G12), pp. 65-77.

Cheung, Y., Lee, P. and Xie, K. 1991. Some remarks on two and three dimensional consolidation analysis of sand-drained ground. *Computers and Geotechnics,* 12**,** 73-87.

Hansbo, S. 1981. Consolidation of fine-grained soils by prefabricated drains. *Proc. of 10th ICSMFE, 1981,* 3**,** 677-682.

Hird, C., Pyrah, I. and Russel, D. 1992. Finite element modelling of vertical drains beneath embankments on soft ground. *Geotechnique,* 42**,** 499-511.

Indraratna, B., Bamunawita, C., Redana, I. and Mcintosh, G. 2003. Modelling of prefabricated vertical drains in soft clay and evaluation of their effectiveness in practice.

Indraratna, B. and Chu, J. 2005. *Ground Improvement—Case Histories,* London, UK, Elsevier.

Indraratna, B., Perera, D., Rujikiatkamjorn, C. and Kelly, R. 2014. Soil disturbance analysis due to vertical drain installation. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering,* 168**,** 236-246.

Indraratna, B. and Redana, I. 1997. Plane-strain modeling of smear effects associated with vertical drains. *Journal of Geotechnical and Geoenvironmental Engineering,* 123**,** 474-478.

Indraratna, B. and Redana, I. 2000. Numerical modeling of vertical drains with smear and well resistance installed in soft clay. *Canadian Geotechnical Journal,* 37**,** 132-145.

Indraratna, B., Rujikiatkamjorn, C., Kelly, R. and Buys, H. 2012. Soft soil foundation improved by vacuum and surcharge loading. *Proceedings of the ICE-Ground Improvement,* 165**,** 87-96.

Indraratna, B., Rujikiatkamjorn, C. and Sathananthan, I. 2005. Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. *Canadian Geotechnical Journal,* 42**,** 994-1014.

Itasca Consulting Group Inc. 2008. *FLAC-Fast Lagrangian Analysis of Continua, Ver. 6.0*, Minneapolis, MN (USA).

Kelly, R. and Wong, P. 2009. An embankment constructed using vacuum consolidation. *Australian Geomechanics,* 44**,** 55.

Parsa-Pajouh, A., Fatahi, B., Vincent, P. and Khabbaz, H. 2014. Trial Embankment Analysis to Predict Smear Zone Characteristics Induced by Prefabricated Vertical Drain Installation. *Geotechnical and Geological Engineering,* 32**,** 1187-1210.

Ngo, D.H. Horpibulsuk, S. Suddeepong, A. Hoy, M. Udomchai, A. Doncommul, P. Arulrajah A. 2020. Consolidation behavior of dredged ultra-soft soil improved with prefabricated vertical drain at the Mae Moh mine, Thailand. *Geotext. Geomembranes*, 48 pp. 561-571.

Nguyen, T. T., Indraratna, B. & Rujikiatkamjorn, C. 2018. A Numerical Approach to Model Biodegradable Vertical Drains. Environmental Geotechnics, Online First 1-9.

Rujikiatkamjorn C., Indraratna, B. and Chu, J. 2008. 2D and 3D Numerical Modeling of Combined Surcharge and Vacuum Preloading with Vertical Drains. *Intl. J of Geomechanics*, ASCE, 8(2), 144-156.

Rujikiatkamjorn, C., Ardana, M., Indraratna, B. and Leroueil, S. 2013. Conceptual model describing smear zone caused by mandrel action. *Géotechnique,* 63**,** 1377.

Zhu, G. and Yin, J.-H. 2000. Finite element consolidation analysis of soils with vertical drain. *International Journal for Numerical and Analytical Methods in Geomechanics,* 24**,** 337-366.

Table 1: Conversion of permeability and size of smear zone for numerical models

Problem	$d_w = 2b_w$ (mm)	$d_s = 2b_s$ (mm)	$d_e = 2B$ (mm)	k_h (m/s)	$\frac{k_h}{k_s}$	n	s	α	β	$\frac{k_{hp}}{k_h}$	$\frac{k_{sp}}{k_{hp}}$	$d' = 2b'$ (mm)
Unit cell in Sydney soft clay	50	170	450	10^{-10}	3	9	3.4	0.181	0.346	0.461	0.214	106
Multidrain in Sydney soft clay	50	300	1000	10^{-10}	3	20	6	0.241	0.631	0.297	0.242	234
Multidrain in Ballina plastic clay	34	570	1000	10^{-9}	1.7	29	17	0.054	0.568	0.253	0.521	500

Table 2: Material parameters for Ballina soft clay in Soft Soil model

C_c	C_s	p'_c (kPa)	γ (kN/m^3)	e_o	K_o	c' (kPa)	ϕ'°	k_h (m/s)	k_v (m/s)
1.31	0.14	20	14.5	2.9	0.75	5	25	10^{-9}	8×10^{-10}

C_c: Compression index, in $e-log\sigma'$ plane, C_s: Swelling index in $e-\log\sigma'$ plane, p'_c: pre-consolidation pressure, γ: Saturated unit weight, e_o: Initial void ratio, K_o: Coefficient of lateral pressure at-rest, c': Drained cohesion, ϕ': Drained friction angle, k_h and k_v : Coefficients of permeability in horizontal and vertical directions

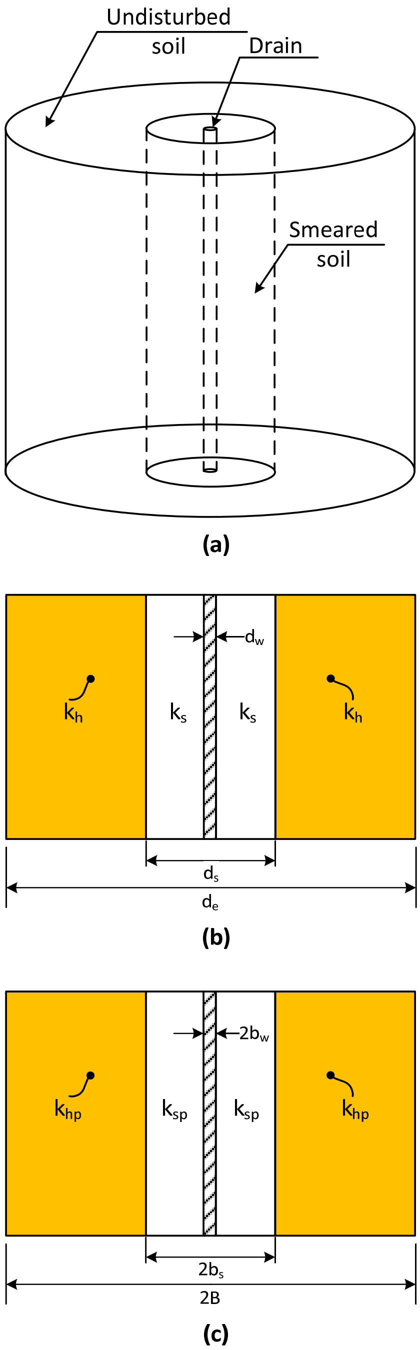


Figure 1: (a) A single drain and surrounding disturbed and undisturbed soils, (b) Unit cell of a drain-soil system in axisymmetric conditions, and (c) Converted unit cell in plane strain conditions

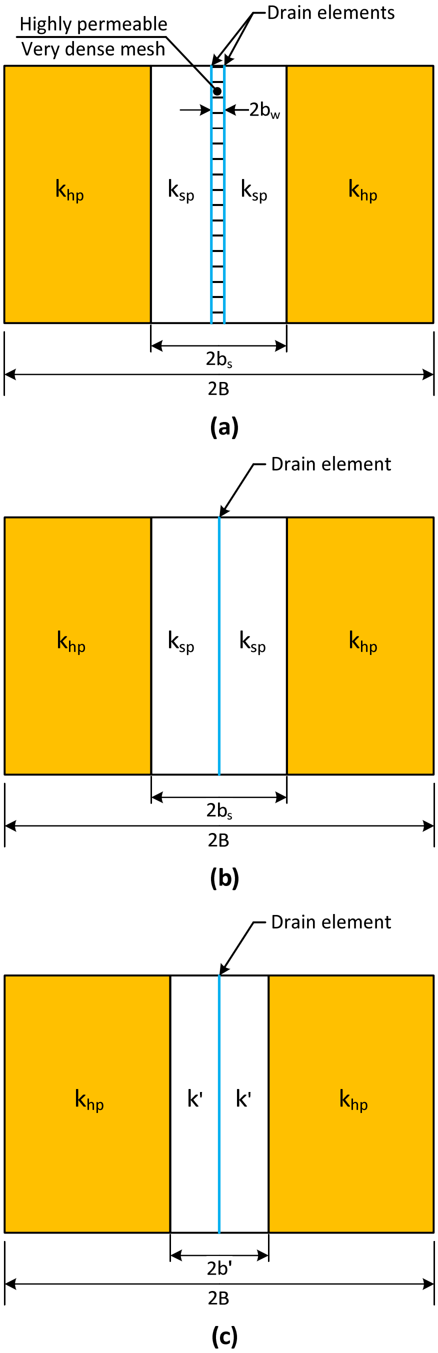


Figure 2: Simulation of plane-strain unit cell using linear drain elements using: (a) ultra-fine elements inside the drain (b) drain elements ignoring the effect of drain size, and (c) proposed scheme using converted size of the smear zone

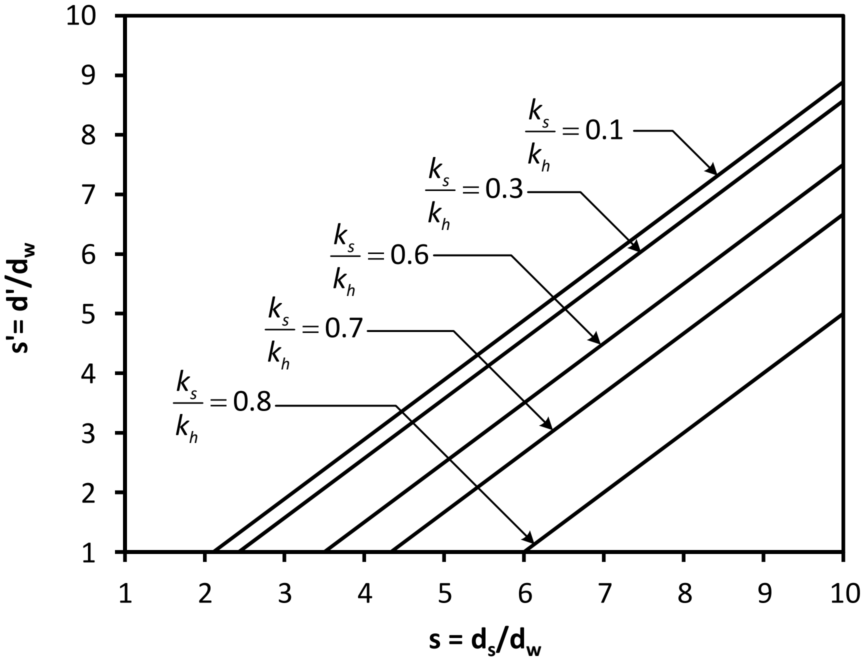


Figure 3: Variation of s' with s for a range of smear zone permeability ratios

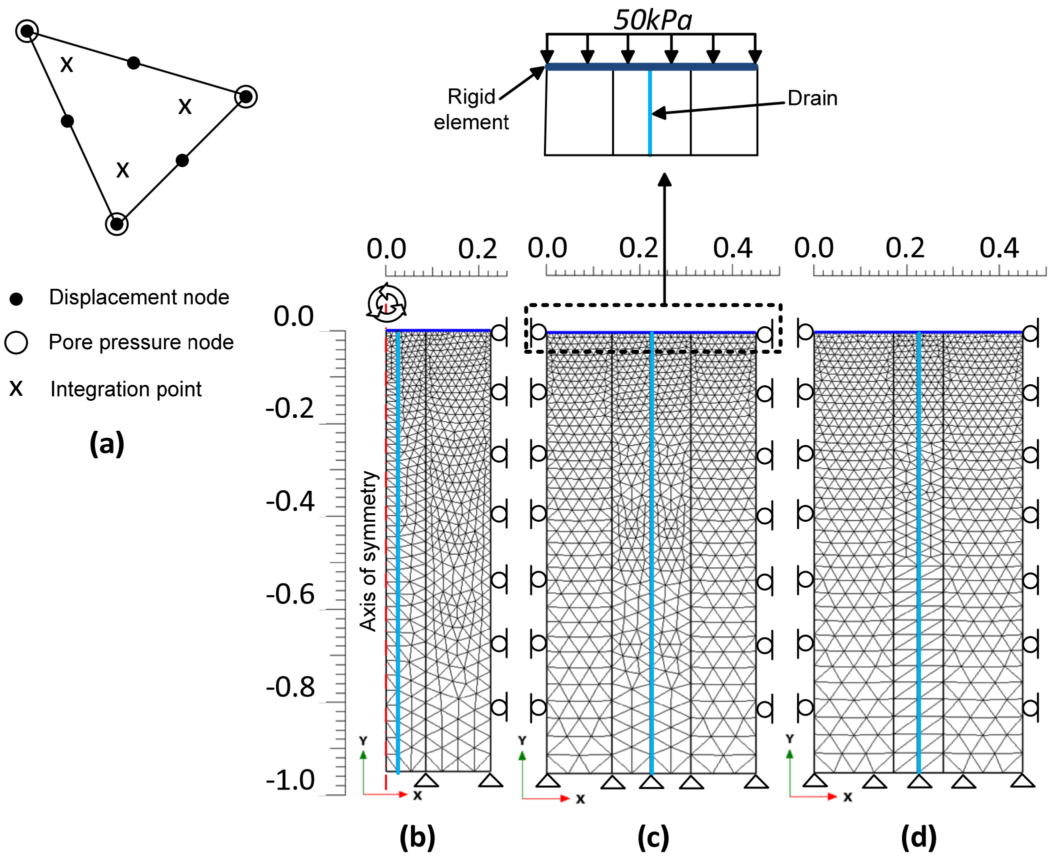
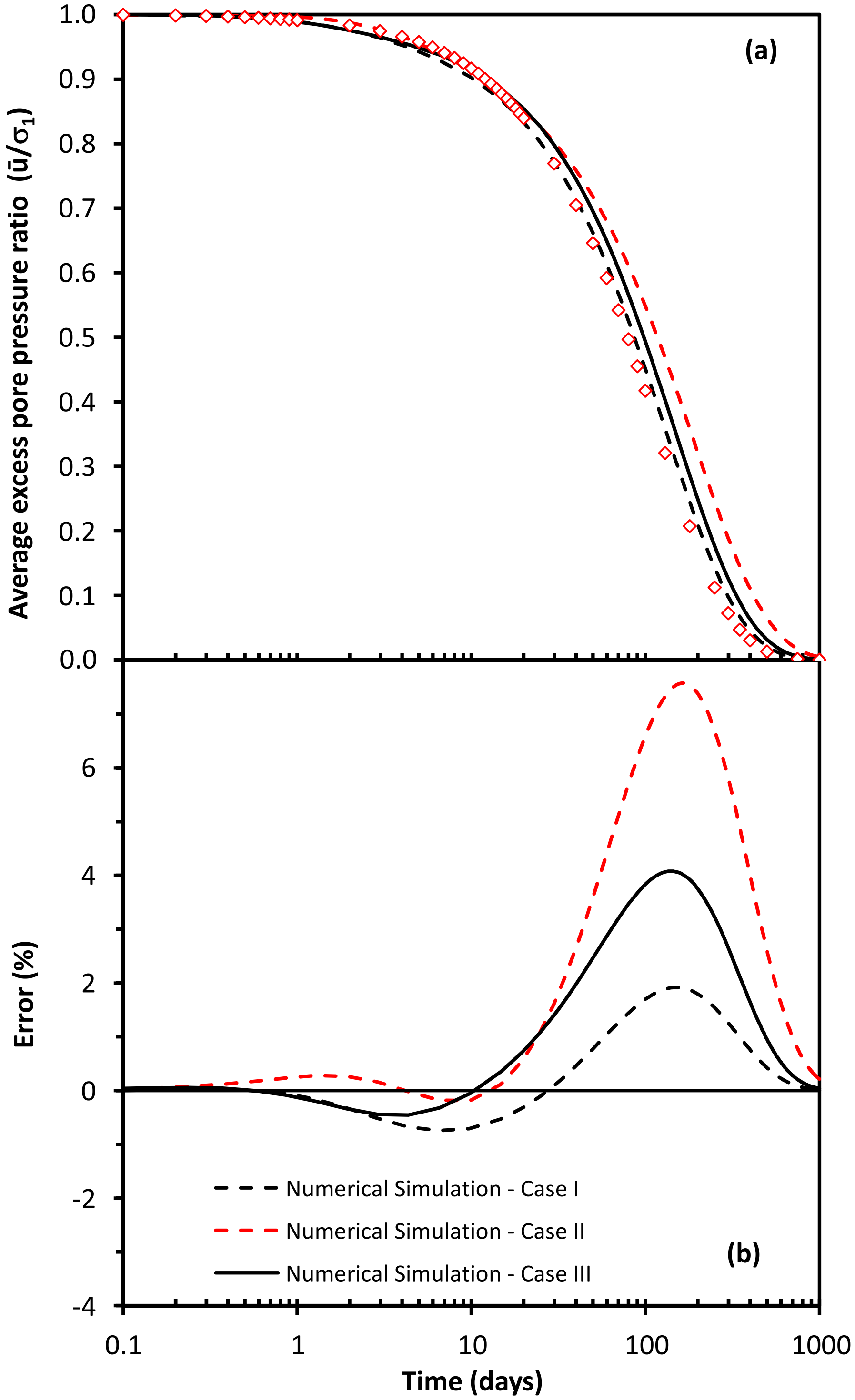


Figure 4: Finite element discretization for unit cell: (a) nodes and integration points for a single 6-node element; (b), (c), and (d) mesh discretization and boundary conditions for Case (I), Case (II), and Case (III), respectively.



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378 **Figure 5: Consolidation responses using different numerical schemes: (a) average excess pore**
379 **pressure curve, and (b) error in calculation of average excess pore pressure in numerical models**
380 **with respect to analytical solution**

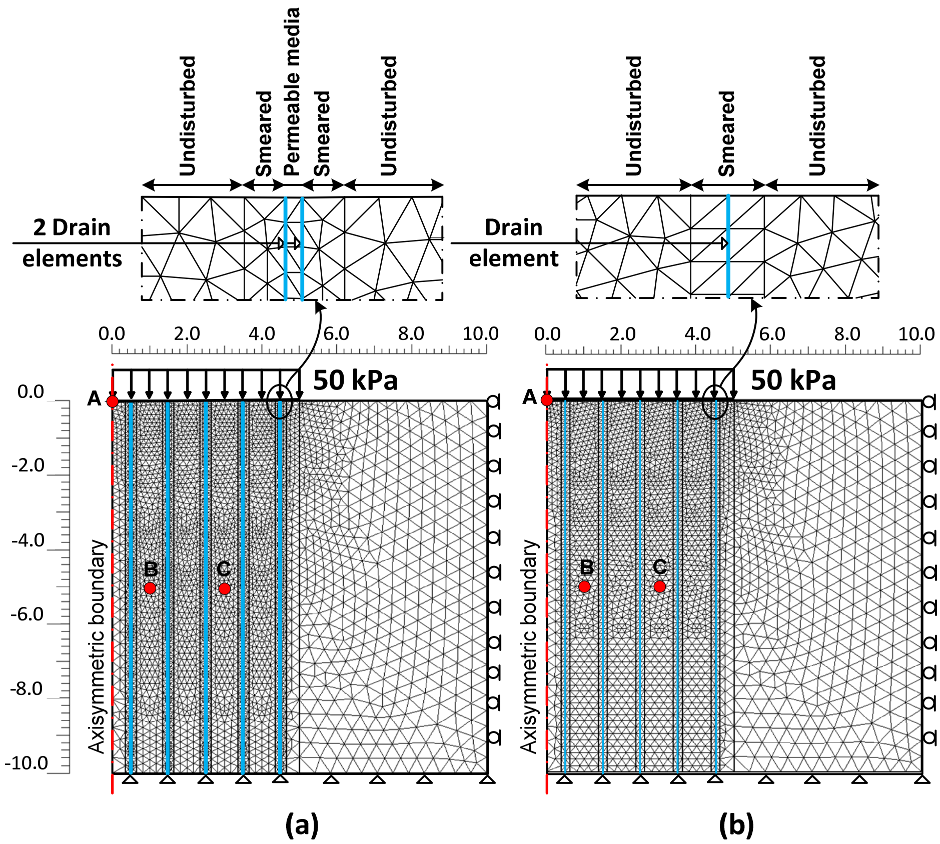

Figure 6: Mesh, boundary conditions and observation points of a multidrain problem: (a) Ideal simulation using two drain elements and a permeable media in between, and (b) Proposed model using single drain element and adjusted size of smear zone

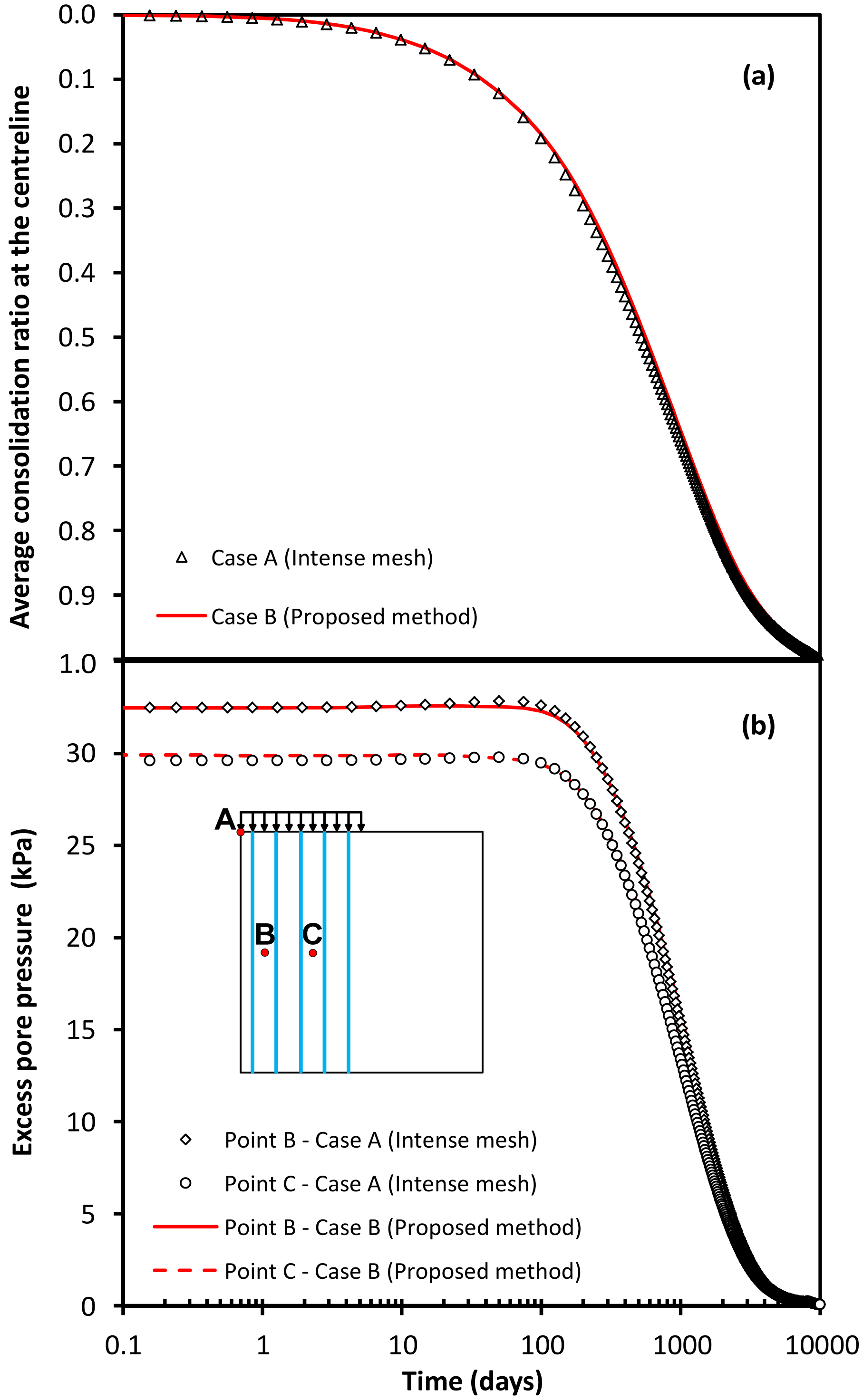

Figure 7: Consolidation responses for multidrain analysis: (a) average consolidation ratio at the model centerline, and (b) excess pore water pressure at points B and C

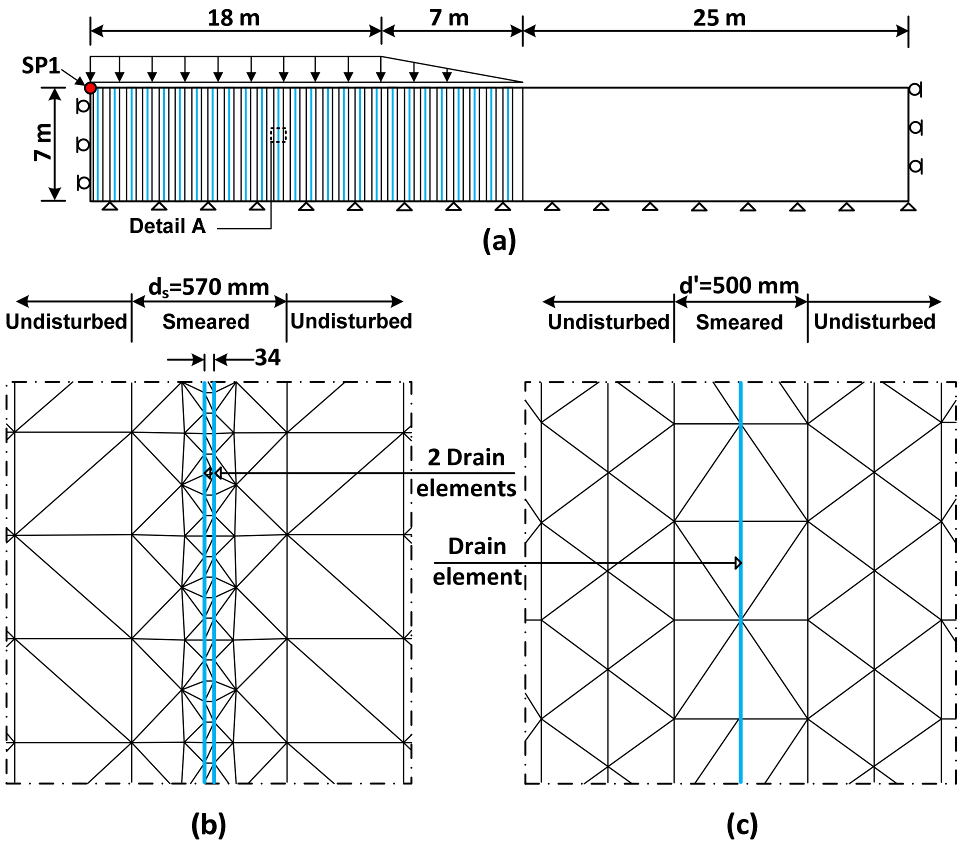

Figure 8: (a) Geometry and boundary conditions of multidrain system in Ballina soft clay, (b) Case (I): ideal mesh using two drain elements and a permeable media in between, and (c) Case (II): a proposed model using single drain element and adjusted size of smear zone

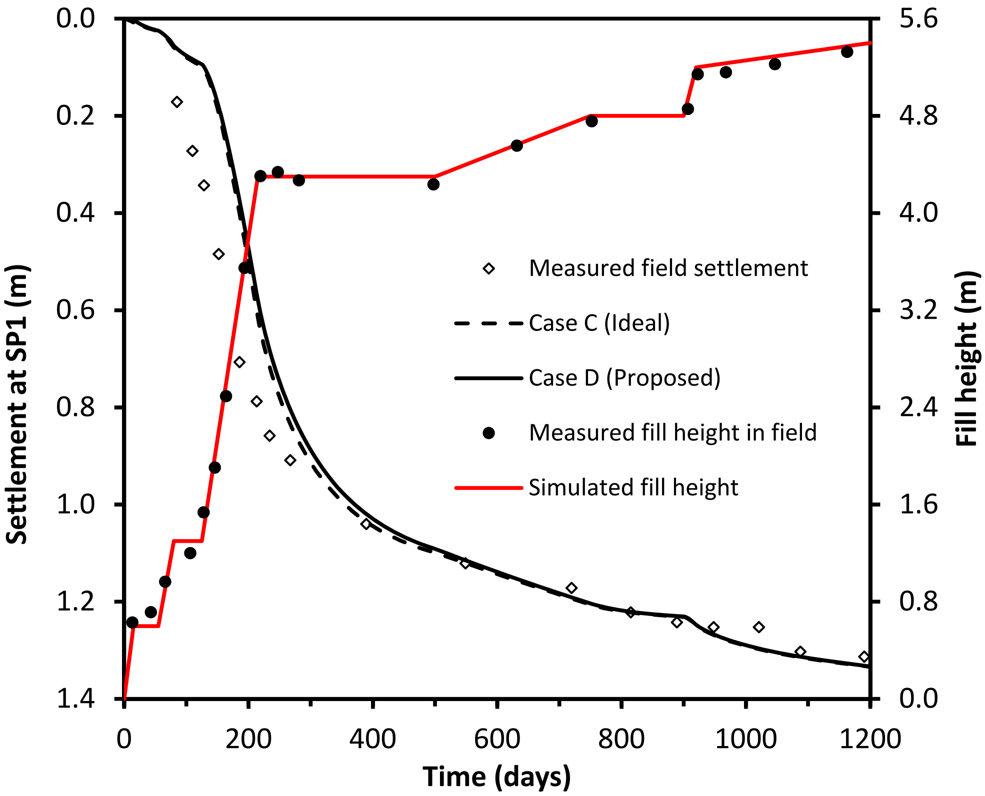

Figure 9: Simulation of Ballina Bypass Section-A trial embankment, loading history, and settlement at the embankment centerline

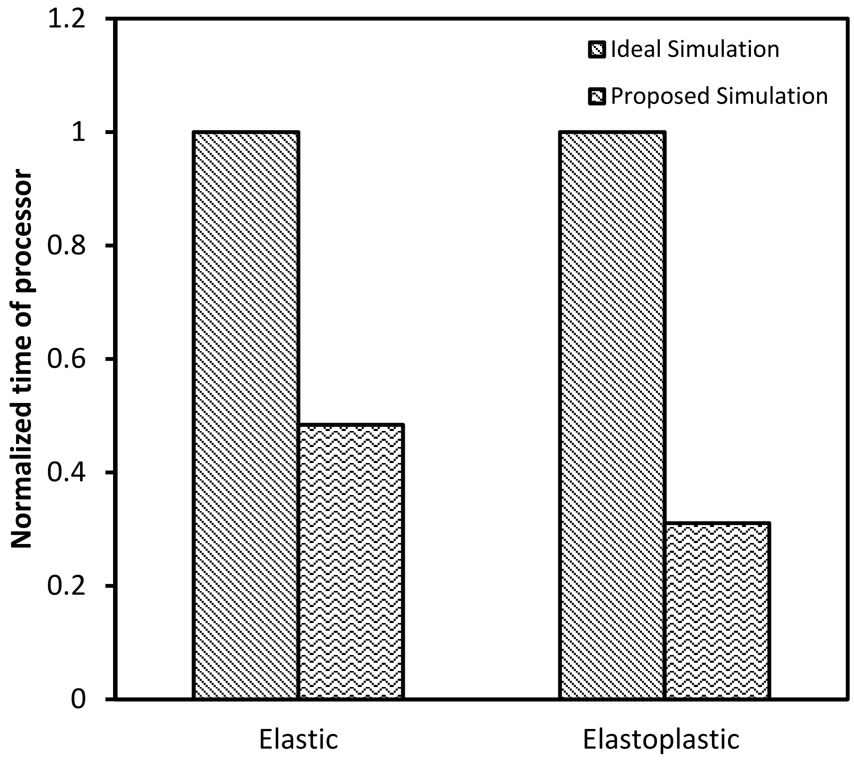

Figure 10: Effect of the proposed scheme on computational time, in comparison with the ideal simulation scheme