**Journal of Building Technology, 2025, Volume 7, Issue 1**
DOI: 10.32629/jbt.v7i1.3622
ISSN Online: 2717-5103
ISSN Print: 2705-1390

# Mitigation of Damage Caused by Cracks in the Soil

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**Abstract:** The design of a trench of granular material is shown. This design can be used to mitigate the damages caused by cracks that have appeared in the soil in certain zones of Mexico City. The most destructive cracks are associated with differential settlements due to the regional subsidence of Mexico City and can show escarpments of considerable height. The proposal solution consists of constructing a trench of sand on the crack line, called "Dissipative box of unit deformations". The trench behavior is assessed by means of numerical simulations with discontinuous media approach using the discrete element method. It is drawn that the unit deformations (differential settlements/horizontal distances) on the surface decrease when the depth of trench increases. The simulations allow to obtain an optimal design of the dissipative box distributing the vertical displacements in a sufficient horizontal length so that the escarpment disappears and is replaced by a surface with moderate inclination. In this way, a road affected by a crack can continue open to traffic. Continuous media analyses are also presented, and their results are compared with those of the discrete media approach. Some conclusions and practical recommendations for the mitigation of damage caused by cracks are given.

**Key words:** crack; trench; granular medium; dissipative box; soil; unit deformations

## 1. Introduction

For several decades, cracks have been observed in the ground of Mexico City, primarily in the municipalities of Iztapalapa, Tláhuac, Xochimilco, and Milpa Alta. These cracks cause damage to buildings, public services, and roads, endangering the well-being of residents and requiring significant maintenance costs.

A crack can be initiated by any condition that generates significant tensile stresses in the ground (Auvinet, 2010; Auvinet et al., 2013a, 2013b, 2017, 2018). Certain mechanisms, such as hydraulic fracturing, facilitate the generation and propagation of cracks. However, the most significant and destructive cracks are caused by differential settlements associated with regional subsidence due to water extraction in the subsoil of the Valley of Mexico. The cracking phenomenon has worsened following the September 2017 earthquakes, and some steps exceeding 1 m in height have been observed. Cracks become more problematic when they erode and widen, so it is preferable to seal them immediately to restore ground continuity.

Regional subsidence cracks are characterized by steps with the lower part facing the area of greatest settlement (Figure 1) and are very difficult to control in practice (Auvinet, 2017).

**Figure 1.** Crack with step on a road in Mexico City.

To reduce damage to buildings, public services, and roads, the presence of cracks must be considered in the design. The use of joints that allow the crack to pass freely has proven useful for walls and fences. However, these damage mitigation measures have been implemented empirically, and no design-oriented studies have been conducted for these solutions. Mitigation measures for damage caused by crack propagation must be based on robust structural and geotechnical solutions. Among the latter are those based on the dissipation of the step at the ground surface to mitigate damage to streets and roads. The solutions presented in this paper are exclusively related to the problem of stepping at the ground surface. The proposed solutions are evaluated through numerical analyses based on the discontinuous media approach (discrete element method), which are compared with those that can be performed using continuum mechanics (finite element method).

**2. Proposed Solution**

It has been observed that a continuous material on the ground surface, such as road pavement, exhibits brittle failure in the presence of differential subsidence (Figures 1 and 2a), causing an abrupt step. The main concept of the proposed solution is to replace the natural soil surface with granular material, such as sand or gravel without fines, that does not transmit stress and whose grains rearrange themselves when the crack moves (Figure 2b).

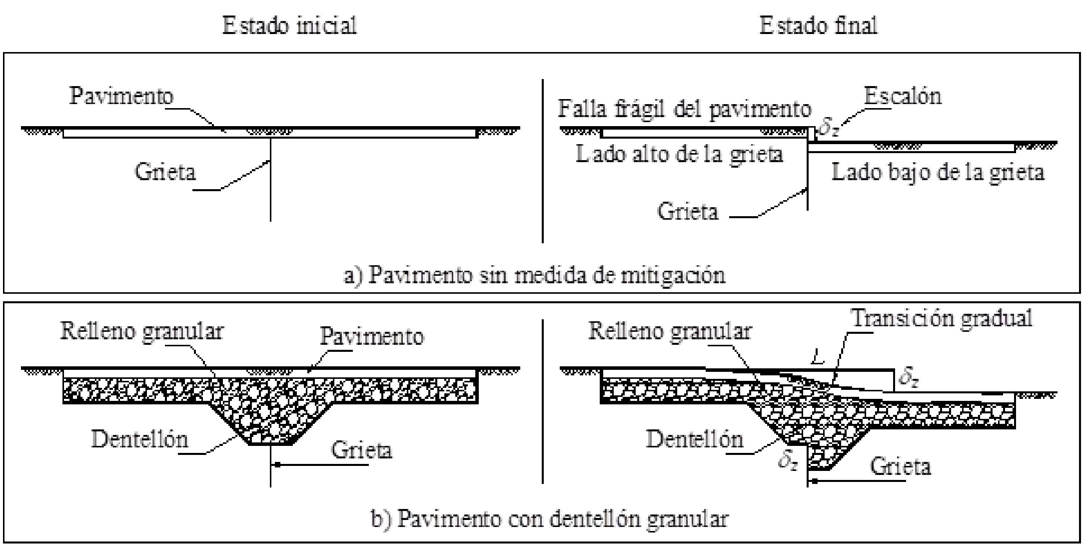


**Figure 2.** Hypothetical behavior of a tooth for differential subsidence control.

This solution is later evaluated through numerical simulations with discrete element models and traditional numerical models with finite elements. In the analyses, the existence of a crack in a roadway is considered, and a dent is added to the top of the crack.

The proposed geometry for the analysis model is presented in Figure 3. The horizontal dimensions of the model are sufficient to allow the free development of settlements. The simulation of the formation of a step in the crack consists of imposing a vertical displacement $\delta_z$ on the right half of the model and restricting the displacement on the left side. Vertical displacements $\delta_z$ in the crack are considered at 0.1, 0.2, and 0.3 m.

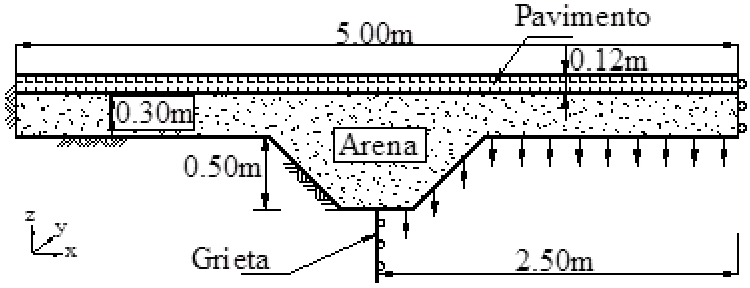


**Figure 3.** Model with sand dent.

**3. Modeling with a Discontinuous Media Approach**

The discrete element method (DEM) (Cundall and Strack, 1979) simulates the mechanical interaction between a set of independent particles according to a rheological contact model. In the case of sand, the interaction forces at grain contacts are governed by surface friction. The particles are represented by rigid disks or spheres with a density $\rho$ = 2600 kg/m$^3$ and a friction coefficient $\mu$ = 0.7 (equivalent to an interparticle friction angle $\varphi\mu$ = 35°). Two-dimensional (2D) and three-dimensional (3D) simulations are performed.

To simulate the problem of interest, particles are selected according to a relatively uniform granulometry (uniformity coefficient Cu = 2), are deposited by gravity, and the sample is allowed to reach equilibrium. The surface is leveled, and the particles representing the pavement are placed (Figure 4). Subsequently, to simulate an increase in the crack step, the right side of the model is shifted downward to a given $\delta_z$ value. The displacement speed is very low to avoid inertial effects.

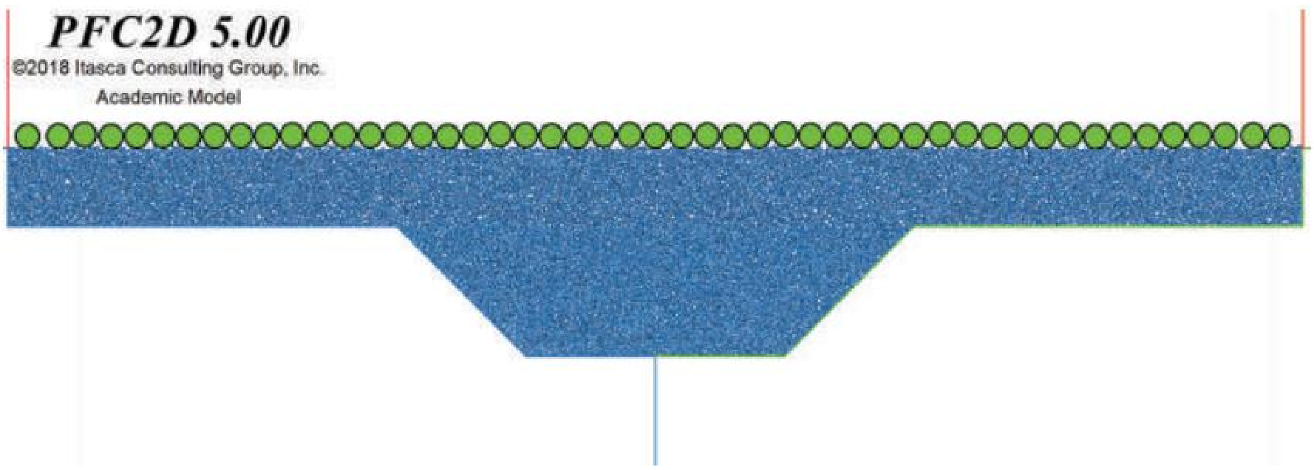


**Figure 4.** 2D DEM model with sand dent.

Through trial and error, it was determined that the appropriate slopes for the dent are 1:1. The base width can be the minimum allowed by the excavation tool. It is advisable for the dent to be horizontally centered over the crack.

Figure 5 shows the vertical displacements of the particles. It can be seen that at the apex of the crack, there is a step, but the surface has a gentle slope, as assumed in Figure 2b. This is a result of the individual movements of the sand particles.

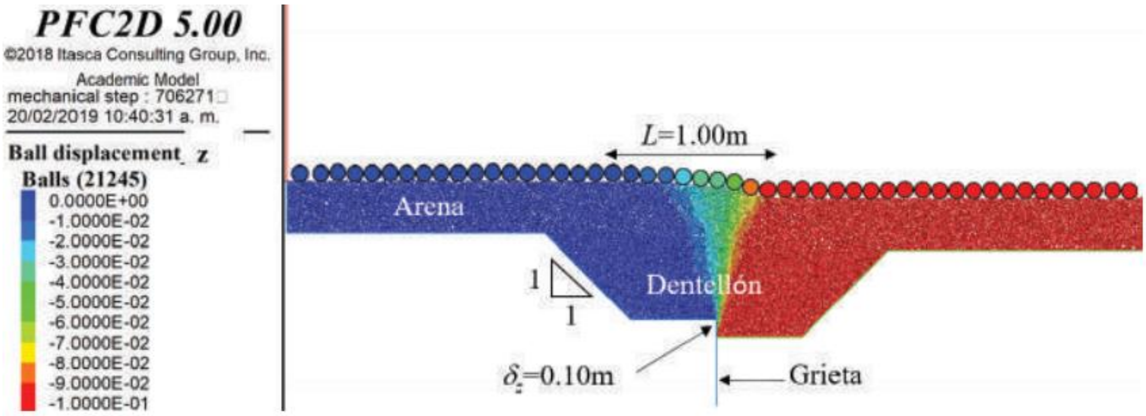


**Figure 5.** Vertical displacements for $\delta_z = 0.10$ m. 2D DEM model with sand dent.

It is also observed that, in most of the models, the particles retain their relative positions. On the high side of the crack, the particles remain static ($\delta_z = 0$), and on the low side, almost all particles descend along with the underlying moving boundary ($\delta_z = 0.1$ m).

Differential vertical displacements occur in the area near the crack. Figure 5 shows that the horizontal length $L$, over which the differential vertical displacements are distributed, increases vertically. The "V" shape of the colors with equal vertical displacement indicates that the deeper the crack (greater thickness of the granular dent), the smaller the unit strain $\delta_z/L$ at the ground surface.

Considering a granular dent 0.5 m deep and a crack step $\delta_z = 0.1$ m, at the crack apex $L = 0$, while at the model surface, $L = 1.00$ m. Therefore, the unit strain $\delta_z/L$ is infinite in the crack, but at the model surface it is 0.10. For these calculations, vertical differential displacements less than 0.001 m are neglected.

Different crack positions at the base of the indentation and different values of the interparticle friction coefficient in the range $\mu \in (0.5, 0.7)$ were tested. In all cases, the model surface is approximately the same. From the above, it is concluded that the reduction in unit strains is primarily controlled by the indentation depth.

Considering that grains have an additional degree of freedom in three dimensions, more realistic results can be expected from 3D simulations. Figure 6 shows the initial state of a three-dimensional analysis model.

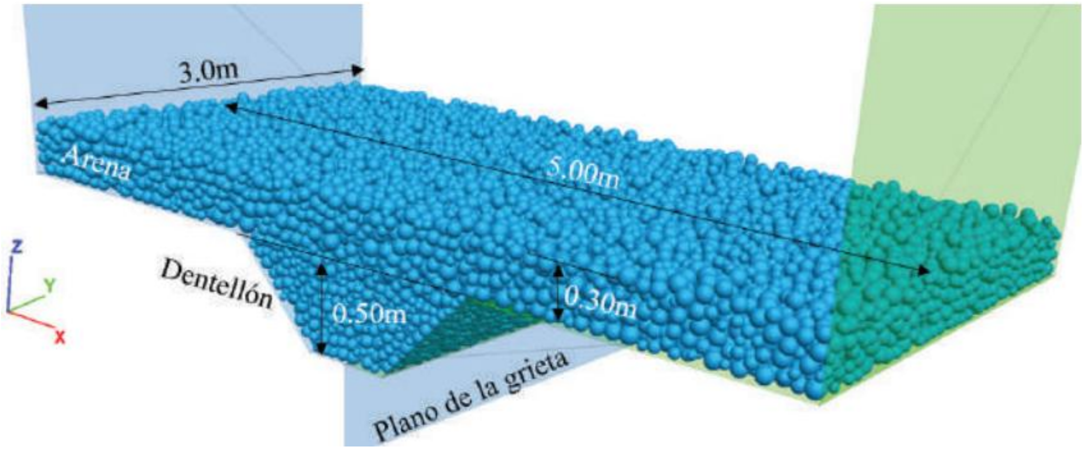


**Figure 6.** 3D DEM model with granular dent.

Repeating the case with $\delta_z$ = 0.10 m (Figure 7) with the 3D model, $L$ = 1.70 m is obtained at the surface and therefore $\delta_z/L$ = 0.06. The result is therefore more favorable than in the two-dimensional case. This can be understood if one takes into account that, in regular arrangements of discs of equal diameter, the porosity can vary by 12.2% (from 9.3 to 21.5%), while in spheres of equal size, the porosity can vary by 21.7% (from 25.9 to 47.6%), that is, there is greater freedom of movement of the grains in three dimensions than in two.

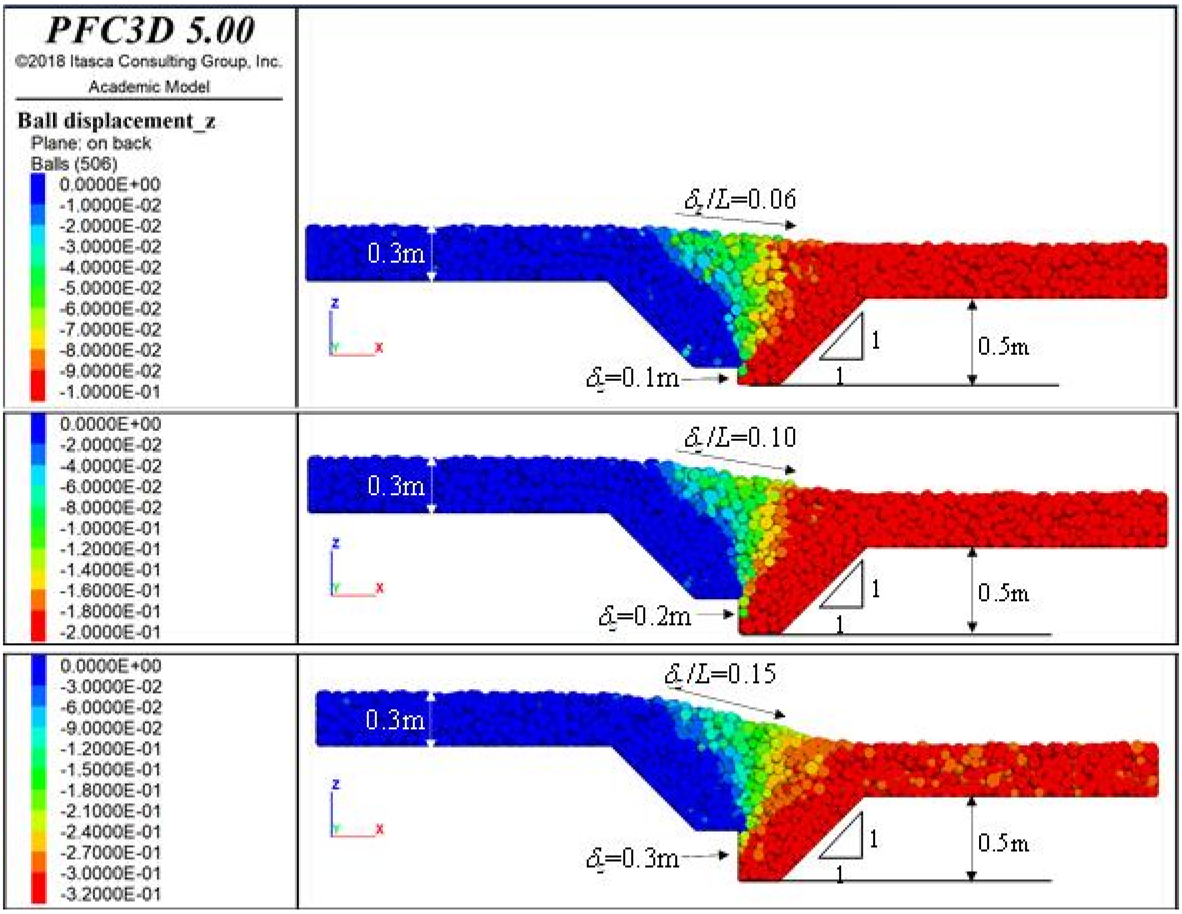


**Figure 7.** Vertical displacements for different $\delta_z$ values. Longitudinal sections in the 3D DEM model with a 0.5 m deep dent.

For vertical crack displacements $\delta_z$ = 0.2 m and $\delta_z$ = 0.3 m, the model surface yields $\delta_z/L$ = 0.10 and $\delta_z/L$ = 0.15, respectively. Figure 7 shows that, as the height of the crack step increases, the length of the inclined surface remains approximately constant.

It can be seen that the differential vertical displacements propagate more toward the high side of the crack. This is because the particles on the low side invariably follow the movement of the lower boundary, but the particles on the high side are partially supported by the fixed boundary and partially by the particles on the low side, which are moving downward.

Once the permissible $\delta_z/L$ value is exceeded (0.15 on vehicle ramps according to CDMX, 2017), maintenance work will be necessary, consisting of removing the roadway pavement, leveling the surface, and replacing the overlay.

Depending on the rate of increase of the crack step and the importance of the road surface, in practice, a different depth of the granular indentation can be adopted. For example, Figure 8 shows the vertical displacements for a 1 m deep indentation, showing that tolerable strains are obtained even for a 0.3 m step.

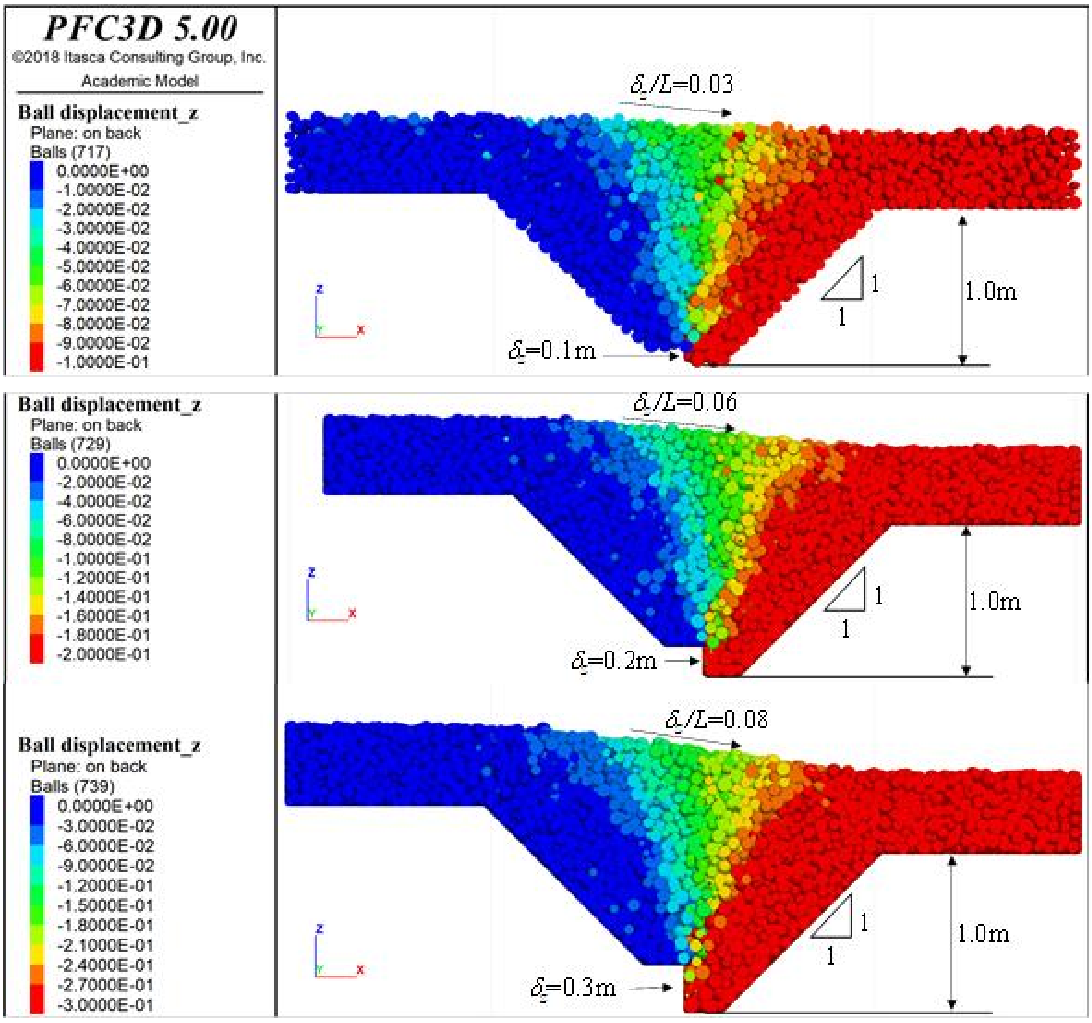


**Figure 8.** Vertical displacements for different $\delta_z$ values. Longitudinal sections in the 3D DEM model with a 1.0 m deep dent.

**4. Modeling with a Continuum Media Approach**

For the finite element analysis, a Mohr-Coulomb elastoplastic constitutive model is considered. A volumetric weight of $\rho$ = 20 kN/m$^3$ is accepted, with elastic parameters: $E$ = 18,000 kPa and $\upsilon$ = 0.35, and plastic parameters: $\varphi$ = 25° and $c$ = 0. To compare the effectiveness of the proposed solution (strain-dissipating box), the distribution of differential settlements on the ground surface is analyzed for each of the three proposed displacements ($\delta_z$ = 0.1 m, 0.2 m, and 0.3 m).

After a parametric analysis for different values of the angle of internal friction ($\varphi$), it was concluded that the analysis of the sand box using continuum media can be better modeled by considering the extreme case in which the angle of internal friction is zero ($\varphi$ = 0). Thus, the Mohr-Coulomb criterion is reduced to the Tresca criterion (Jones, 2009) for maximum shear stress $\tau_{max}$. Based on the boundary conditions of the numerical model, the imposed displacements induce a deconfinement in the material and generate a shear stress at the crack line. This behavior can be represented by an extensional stress state, as shown by Biarez (1961). For finite element analysis, and according to the Tresca criterion, it is necessary to establish a plastic flow (stress-strain relationship) with a yield stress $\sigma_y$ (elastic limit stress), interpreted as a shear stress resistance $\tau_{max}$ whose magnitude depends on the imposed displacement $\delta_z$. The Tresca criterion avoids involving parameters such as $\varphi$ and $\varphi$, which, for the study of sand boxes with continuum media, can lead to unrealistic results.

From the analysis results, the vertical displacements on the box surface were graphed for the three boundary conditions ($\delta_z$ = 0.1, 0.2 and 0.3 m) and for the two indentation depths (0.50 m and 1.00 m). Figures 9 and 10 show the results of the influence of the indentation depth on the horizontal distance L on the surface where the differential settlements are distributed. For example, with a displacement $\delta_z$ = 0.1 m, the unit strain on the surface is $\delta_z/L$ = 0.06 and $\delta_z/L$ = 0.03, for 0.5 m and 1.0 m indentation depth, respectively. It is observed that the surface differential settlements are distributed over a length of 1.6 m for the 0.5 m deep tooth, while for the 1.0 m deep tooth the length is 3.0 m. The greater the depth of the sandbox, the lower the $\delta_z/L$ at the surface. Therefore, the box efficiency is a function of its depth. Likewise, it is observed that the horizontal distances $L$ where the settlement dissipates are similar to those obtained with the discrete element analyses, which are 1.70 m and 3.60 m for the 0.5 m and 1.0 m depth of the tooth.

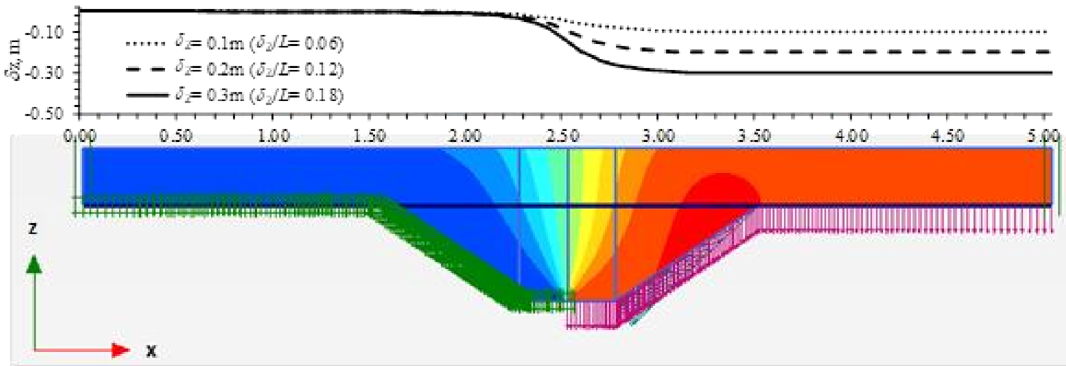


**Figure 9.** Surface settlements for imposed vertical displacements of $\delta_z$ = 0.10, 0.20, and 0.30 m. Dent depth 0.50 m.

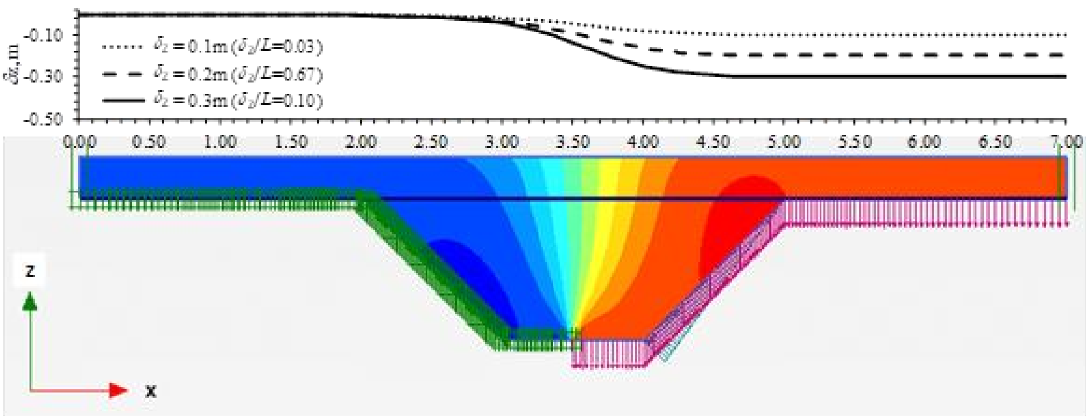


**Figure 10.** Settlements on the sandbox surface for imposed vertical displacements of $\delta_z$ = 0.10, 0.20 and 0.30 m. 1.0 m deep indentation.

**5. Conclusions and Recommendations**

To mitigate problems in roadways associated with step cracks, the placement of a granular indentation on the soil surface is proposed. This idea is based on the fact that granular materials, such as sand, do not transmit stresses and their constituent particles can change their relative positions within the medium, adapting to external movements.

Of the methods used, the discrete element method is considered the most appropriate for analyzing the problem, as it explicitly takes into account the discontinuous nature of granular media. It was observed that two-dimensional simulations lead to conservative designs. Two-dimensional models facilitate calculations, but they considerably underestimate the benefits of granular infill. The following important points regarding the strain-dissipating box are presented from the analysis results:

- The granular material allows differential vertical displacements to be distributed over a horizontal length that increases as the thickness of the granular infill increases. That is, the unit strain $\delta_z/L$ at the surface is smaller when the fill thickness is greater.
- The particles maintain their relative positions when they are at a horizontal distance from the crack equal to or greater than the thickness of the granular fill.
- Considering the two previous points, it is possible to optimize the volume of excavation and fill by constructing a sand indentation centered in the crack. The recommended slopes for excavation are 1:1 to prevent the boundaries from interfering with the rearrangement of the sand grains.
- The bottom of the indentation can be as wide as a backhoe bucket (0.5 m).
- Depending on the importance of the road and the desired time between maintenance operations, the depth of the sand indentation can be chosen. On main roads, deeper indentations should be considered.
- In areas with light traffic, the continuous pavement could be replaced with a cobblestone-based surface. Discontinuities in the paving stone can contribute significantly to the distribution of unit strains.

Sandbox modeling is an independent particle problem governed by an interparticle interlocking mechanism. With continuous media, it is difficult to represent the behavior of granular media because of the friction angle $\varphi$ and the dilatancy angle $\varphi$. However, the Tresca criterion, which assumes $\varphi = 0$, facilitates modeling sandbox behavior. The analysis confirms that the depth of the indentation influences the magnitude of the horizontal length where settlements are distributed.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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