# Uncertainty of Model Parameters in PSDDF for Coastal Restoration

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**Abstract**: Sediment (mud and sand) from man-made diversions of the Mississippi River, dredging effluent, and other sources is being used to conserve and create land to protect the Gulf Coast. The long-term settlement prediction of these newly deposited sediments is necessary to ensure the confined dredged disposal areas, coastal restoration, and marsh creation projects protect people and their property, wetlands, and various infrastructure over the design/service life. Long-term settlement predictions are usually made with the software Primary Consolidation, Secondary Compression, and Desiccation of Dredged Fill (PSDDF). PSDDF is a 1D nonlinear numerical model that accounts for settlement due to self-weight and surcharge induced consolidation, secondary compression, and desiccation. This paper uses a hypothetical case study to estimate the dredged fill height necessary to maintain a surface elevation of 1.5 ft for the next 20 years. Because there is uncertainty in the hydraulic conductivity and compressibility relationships, a reliability analysis is performed to quantify the effect on long-term settlement predictions. The uncertainty analysis indicates that the void ratio-effective stress and void ratio-permeability relationships influence the surface settlement more than the other input parameters for the dredged sediment.

## INTRODUCTION

The thickness of dredged fill gradually decreases via sedimentation, primary consolidation, secondary compression, and desiccation. The primary consolidation, secondary compression, and desiccation processes are fully implemented in the microcomputer program Primary Consolidation, Secondary Compression, and Desiccation of Dredged Fill (PSDDF) by Stark et al. (2005a,b). The sedimentation process is completed shortly after dredged material deposition, and therefore is not included in PSDDF because it has little, if any, effect on the long-term storage capacity or service life of a placement area.

PSDDF has been modified and enhanced from the original versions such as Primary Consolidation and Desiccation Dredged Fill (PCDDF) by Cargill (1985) and PCDDF89 (Stark 1991). Major improvements made in PSDDF from the prior versions are (a) consideration of secondary compression, (b) ability to predict settlements of over- or under-consolidated compressible foundation materials, (c) adjustment of the initial void ratio to the void ratio at zero-effective stress in the void ratio-effective stress relations, (d) consideration of less compressible cohesionless materials in the model, and (e) improvement of numerical execution schemes (Stark et al. 2005a).

The model solves for the following governing equation of the consolidation (Gibson et al. 1967):

$$\left(\frac{\gamma_s}{\gamma_w}-1\right)\frac{d}{de}\left[\frac{k(e)}{(1+e)}\right]\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k(e)}{\gamma_w(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right]+\frac{\partial e}{\partial t}=0 \qquad (1)$$

where $\gamma_s$ is the unit weight of solids, $\gamma_w$ is the unit weight of water, $e$ is the void ratio, $k(e)$, is the coefficient of permeability as a function of void ratio, $z$ is the vertical material coordinate measured against gravity, $\sigma'$ is the effective stress, and $t$ is the time.

Eq. (1) is well suited for the prediction of consolidation in thick deposits of very soft, fine-grained soils, such as dredged material, because it provides for the effects of (a) self-weight consolidation, (b) permeability varying with void ratio, (c) a non-linear void ratio-effective stress relationship, and (d) large vertical strains. Because a closed form solution of Eq. (1) is not possible, the model uses a finite difference scheme to solve the above equation using the procedure described by Cargill (1983, 1985). Once the void ratio-effective stress and void ratio-permeability relationships are defined, the model computes the void ratio in the consolidating layer at any specified time using an explicit finite difference scheme. The model computes consolidation of the layer until the start of desiccation, after which it assumes normal consolidation until complete drying has occurred in the dredged material layer or a new material layer is placed.

The major input parameters governing primary consolidation in PSDDF are the void ratio-effective stress and void ratio-permeability relations obtained from a series of laboratory consolidation tests on the dredged fill and foundation materials. Cargill (1986) describes laboratory test procedures to obtain these relations. The specific gravity of solids, initial void ratio, and desiccation characteristics of the dredged material are also required. In addition, climatological data, anticipated dredging schedules and quantities, water table elevated, and drainage characteristics of the containment site are required.

This paper uses a hypothetical case of marsh restoration to estimate settlements of dredged fill. In addition, uncertainty in the input parameters are used to evaluate the reliability of the settlement.

## HYPOTHETICAL CASE STUDY

The case study presented herein is to simulate marsh creation in coastal Louisiana. For example, lower Plaquemines Parish, which is part of the Mississippi River basin, has an annual marsh land loss rate of about 1.3 square miles. The loss of these marshes has exposed significant infrastructure to open water conditions and has made the areas situated nearby less suitable for various wildlife and fish species. Restoring the marshes through deposition of dredged material and the subsequent reestablishment of emergent wetland vegetation will help to protect the back levees from accumulated damage due to elevated water levels and storm surge forces. There are several fringe marsh locations in need of restoration due to the fragmentation of those fringe marshes adjacent to the back of levee bases, which provide critical protection for businesses and residents. The major objective of this restoration project is to use hydraulically dredged soil material obtained from nearby navigation canals to create and nourish marsh in Louisiana for the next 20 years.

Fig. 1 shows the cross-section of the hypothetical case in Louisiana. The cross-section consists of a stratum with a top layer of organic clay (OH), followed by a layer of lean clay (CL), then silty sand (SM), clayey sand (SC), above an impermeable layer of fat clay (CH). Two containment embankments are constructed from the organic clay to an Elev. +1.5 ft. The tidal elevation, signified by the blue color overlying the organic clay, is approximately at Elev. 0 ft. The top of the organic clay layer is Elev. -1 ft. The dredged fill height should be 1.5 ft after 20 years. The input parameters specific gravity ($G_s$), Cα/Cc, Cr/Cc, and OCR used in the analyses are provided in Table 1. Figs. 2(a) and 2(b) provide the void ratio-effective stress and void ratio-permeability relationships, respectively.

**TABLE 1. Summary of soil layers and consolidation input layers (Stark 2014)**

| Soil Layer | $G_s$ | $C_r/C_c$ | $C_\alpha/C_c$ | OCR |
|---|---|---|---|---|
| Dredged Fill | 2.61 | 0.13 | 0.02 | ~1 |
| Organic Clay (OH) | 2.43 | 0.17 | 0.06 | ~1 |
| Lean Clay (CL) | 2.65 | 0.19 | 0.05 | ~1 |
| Silty Sand (SM) | 2.65 | 0.15 | 0.02 | ~1 |
| Clayey Sand (SC) | 2.65 | 0.10 | 0.02 | ~1 |
| Fat Clay (CH) | 2.68 | 0.15 | 0.05 | ~1 |

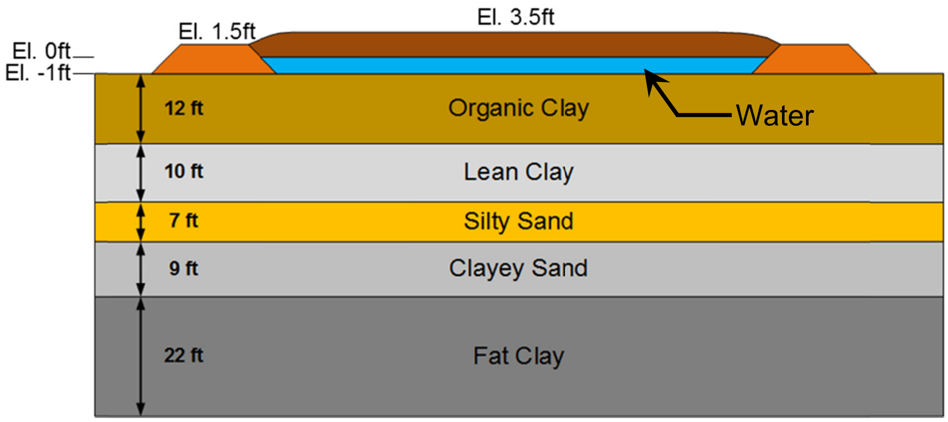
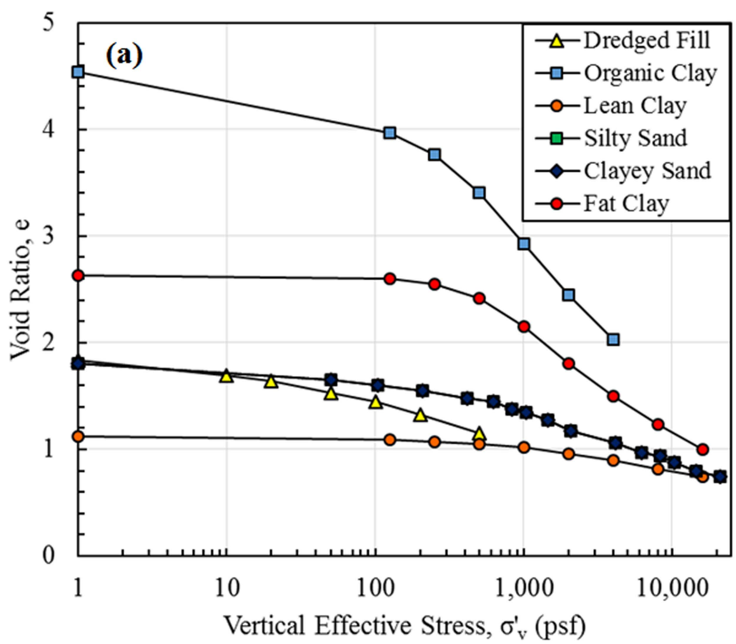



**FIG 1. Plan view of Cells 4 through 7 showing: (a) location of gas extraction wells and stability pins, (b) leachate and composite liner system elevations**



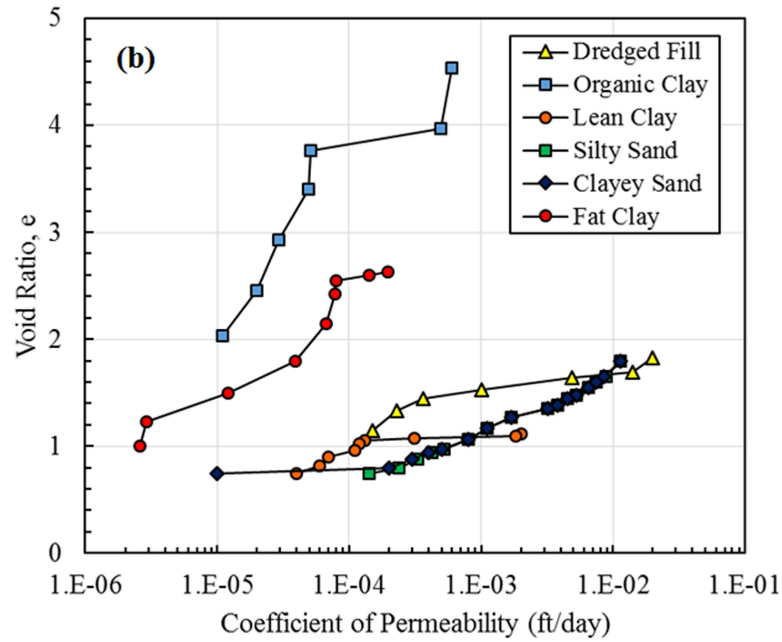



**FIG 2. Marsh restoration soil void ratio relationships for (a) vertical effective stress and (b) coefficient of permeability**

Based on the input parameters, a number of analyses using varying dredged fill heights can be run in PSDDF, which provides output of surface elevation with time. For example, Fig. 3 shows the surface elevation from time 0 days to an elapsed time of 7,300 days (20 years) for the hypothetical case in Fig. 1. The general trend of settlement is a sharp decrease in final elevation after 365 days have elapsed. Afterwards, settlement linearly decreases at a rate of about 0.15 inches/ year. The dredged lifts of 2 ft, 2.5 ft, 3 ft, and 3.5 ft were selected to illustrate the applicability of PSDDF. If the design surface elevation after 20 years of service is 1.5 ft, Fig. 3 indicates that 3 to 3.5 ft of dredged fill is required to meet this criterion. In specific, the surface of 3.5 ft of fill is about 1.85 ft while the other fills are at or below the 1.5 ft threshold. The hypothetical case shows that 3.5 ft of dredged fill is required, with 3 ft of fill resulting in a final elevation near 1.5 ft. However, there is considerable uncertainty in the input parameters, including hydraulic conductivity and compressibility of the dredged fill and foundation layers. The current impact to the design dredged fill elevation by investigating the uncertainty of soil properties is addressed next.

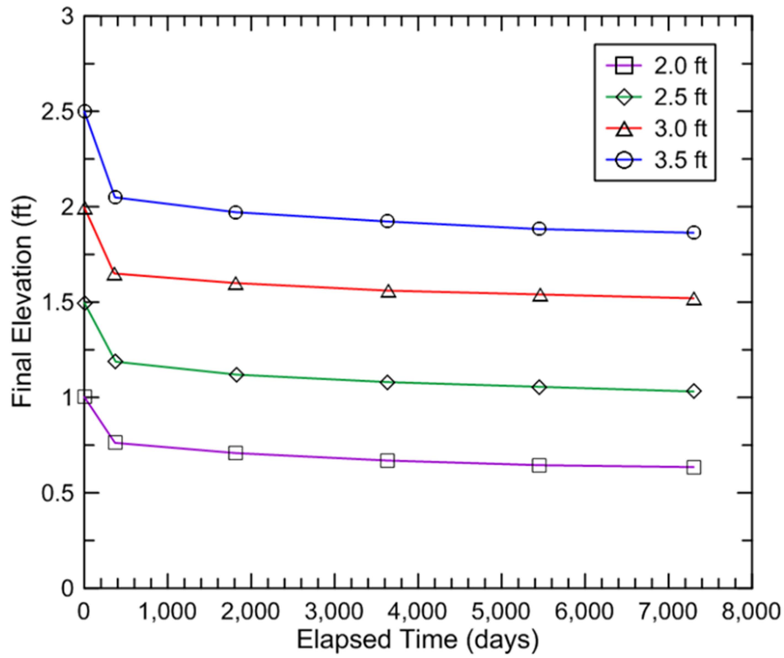



**FIG 3. Design surface elevation with time and varying initial fill heights**

## UNCERTAINTY IN SETTLEMENT PREDICTIONS

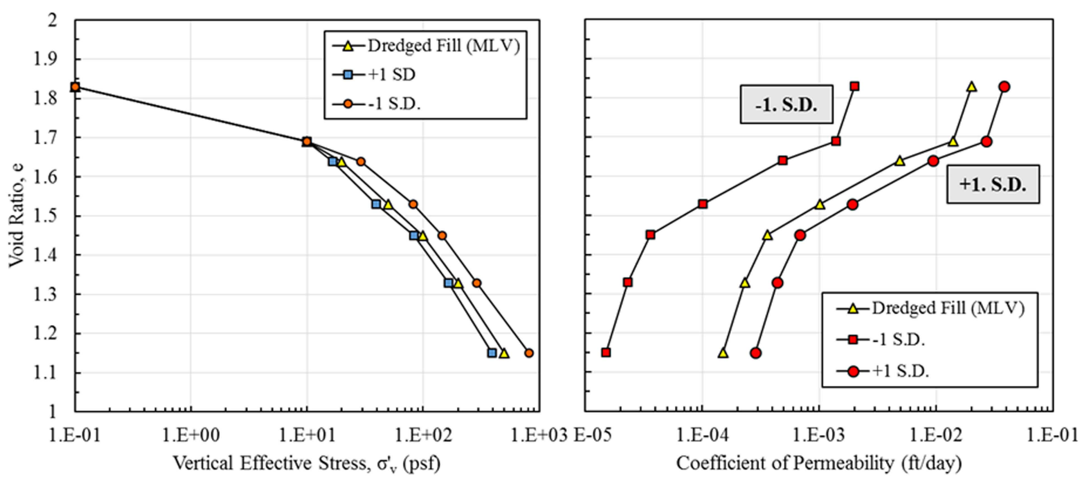
The Taylor Series method can be used to capture the effect of soil variability and differences in test procedures on the factor of safety. In this method, the coefficient of variation (C.O.V.) of soil properties, e.g., hydraulic conductivity, soil compressibility, and saturated unit weight, are used to estimate the uncertainty in the factor of safety (FS). Duncan (2000) provides three examples, including a retaining wall, slope stability, and settlement, to illustrate how uncertainty in engineering properties affects the probability of failure. As a result, the method proposed by Duncan (2000) is applied to capture the variability of soil parameters used in the finite difference consolidation analyses.

Duncan (2000) proposes several procedures to estimate the variable standard deviations impacting the estimated settlements from a surcharge fill. For example, the C.O.V. of saturated unit weight is about 5% (Duncan 2000), so one standard deviation (SD) can be found by multiplying by 5% and the most likely value (MLV). Harr (1984) reports the upper limit C.O.V. is 90% for saturated hydraulic conductivity and about 35% for the compression index ($C_c$).

For the hypothetical case study, the variables used in the uncertainty analysis include specific gravity, recompression index, void ratio-permeability, and void-ratio-effective stress relationships. The C.O.V. for specific gravity is inferred from the C.O.V. of saturated unit weight ($\gamma_{sat}$). For example, the initial void ratio ($e_o$) and specific gravity ($G_s$) are used to calculate the initial unit weight using Eq. (2).

$$\gamma_{sat} = \left(\frac{G_s + e_o}{1 + e_o}\right)\gamma_w \tag{2}$$

Using the C.O.V. of 5% and Eq. (2), ±1 standard deviation of the reported Gs values in Table 1were computed. The C.O.V. for the recompression index is assumed 35% from Harr (1984). For the void ratio-permeability relationship, the CO.V. of hydraulic conductivity (~90%) is used to compute the ±1 standard deviation while maintaining a constant void ratio. In other words, the trends in Fig. 2(b) are shifted to the right or left without changing the void ratio. To compute the ±1 standard deviation of the void ratio-effective stress relationship, the compression index (Cc) for the soil layers in Fig. 2(a) were estimated. Based on the $C_c$ value, the $C_c$ standard deviation was determined using a C.O.V. of 35% (Duncan 2000). With the new Cc values, the void ratio-effective stress trends were approximated. Table 2 summarizes the ±1 standard deviation values determined for each variable and soil layer and subsequently used in the uncertainty analysis.




(a) (b)

**FIG. 4 Variation of (a) void ratio-effective stress and (b) void ratio-permeability**

The Taylor Series method is used to estimate the standard deviation and variance in settlement (S). The standard deviation in settlement ($\sigma_S$) is estimated using the following Taylor Series expression:

$$\sigma_S = \sqrt{\left(\frac{\Delta S_1}{2}\right)^2 + \left(\frac{\Delta S_2}{2}\right)^2 + \left(\frac{\Delta S_3}{2}\right)^2} \tag{3}$$

where ΔS is the change in surface settlement computed for the most likely value (MLV) plus one SD (+1 SD) and the MLV minus one SD (-1 SD) for the parameter in question. The coefficient of variation of settlement ($V_S$) is calculated as:

$$V_S = \frac{\sigma_S}{S_{MLV}} \tag{4}$$

where $S_{MLV}$ is the settlement using the most likely values for each parameter. Table 2 shows the results from the uncertainty analysis. For each variable, the settlement computed using the +1SD and -1SD value is used to determine $\Delta S$. For example, +1SD settlement and -1SD settlement are 0.92 and 1.27, respectively, for horizontal hydraulic conductivity, and the resulting $\Delta S$ is -0.35. After $\Delta S$ is calculated for each variable, Eq. (3) can be used to estimate the standard deviation $\sigma_S$ and Eq. (4) to estimate coefficient of variation $V_S$.

**TABLE 2. Taylor Series uncertainty analysis for PSSDF**

| Variable | Values | Surface Elevation | $\Delta S$ |
|---|---|---|---|
| Specific Gravity, $G_s$ | | | |
| MLV +1 SD | 2.74 | 1.90 | 0.05 |
| MLV -1 SD | 2.48 | 1.85 | |
| $C_r/C_c$ | | | |
| MLV +1 SD | 0.18 | 1.87 | 0.01 |
| MLV -1 SD | 0.08 | 1.86 | |
| Void ratio-effective stress, e-$\sigma'_v$ | | | |
| MLV +1 SD | See Fig. 4(a) | 1.87 | -0.03 |
| MLV -1 SD | See Fig. 4(a) | 1.90 | |
| Void ratio-permeability, e-k | | | |
| MLV +1 SD | See Fig. 4(b) | 1.87 | -0.03 |
| MLV -1 SD | See Fig. 4(b) | 1.90 | |

$$\sigma_S=\sqrt{\left(\frac{0.05}{2}\right)^2+\left(\frac{0.01}{2}\right)^2+\left(\frac{-0.03}{2}\right)^2+\left(\frac{-0.03}{2}\right)^2}=0.03$$

$$V_S=\frac{\sigma_S}{S_{MLV}}=\frac{0.03}{1.87}=1.6\%$$

Based on Table 2, the $\sigma_S$ and $V_S$ are 0.03 and 1.6%, respectively. Although the $S_{MLV}$ is 1.87, the $V_S$ indicates that there is not considerable uncertainty in the surface settlement. As a result, $V_S$ provides a method to incorporate the variability in soil properties to evaluate the probability of the surface settlement becoming lower than Elev. 1.5 ft, i.e., considered the limit state in this scenario. In addition, Table 2 indicates that void ratio relationships play the most important role in settlement uncertainty and that recompression index and $G_s$ impacts are smaller. However, the uncertainty analysis was performed for only dredged fill. There is uncertainty associated with the foundation properties as well. In specific, about 50% of the settlement can originate from the foundation. Therefore, the uncertainty of the organic clay and lean clay should also be considered.

## SUMMARY AND RECOMMENDATIONS

When impounding dredged soils in a placement area, the soil will behave as a slurry, i.e., it will undergo sedimentation and consolidation during reclamation work. It may also undergo desiccation, depending on the environment and operation of the placement area. A hypothetical case in Louisiana shows the design procedure for evaluating the dredged fill necessary to maintain a certain elevation 20 years in the future. Based on the uncertainty analysis, the void ratio-effective stress and void ratio-permeability relations are found to influence the variability of settlement the greatest. However, further investigations are necessary into quantifying the C.O.V. of dredged material. The values used in this analysis are based on soft to stiff soil from literature. In particular, site specific data from Louisiana marsh restoration projects can be used to develop a database decreasing the possibility of failure, i.e., marsh surface drops below the water level.

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