TECHNICAL BULLETIN NO. 6

SETTLEMENT CONTROL FOR EMBANKMENTS AND TRANSPORTATION RELATED STRUCTURES USING GEOPIER® SOIL REINFORCEMENT

This Technical Bulletin discusses the use of Geopier soil reinforcement for support of transportation structures including Mechanically Stabilized Earth (MSE) retaining walls and large embankment fills. The installation of stiff Geopier elements provides a significant increase in the composite stiffness of otherwise soft and compressible foundation soils. Geopier construction using open-graded stone affords radial drainage to the elements. The result of Geopier installation is a significant decrease in both settlement magnitude and duration within the Geopier-reinforced zone. This Technical Bulletin describes design methods used for the reinforcement of poor foundation soils to support transportation structures, such as MSE walls and embankments, using Geopier soil reinforcing elements.

1. BACKGROUND: DESIGNING EMBANKMENTS AND TRANSPORTATION-RELATED STRUCTURES

Without soil reinforcement, the construction of MSE retaining walls and embankment fills on compressible soils can result in significant settlement. Settlement durations may be on the order of months or years before the majority of the settlement is completed, depending on the soil compressibility, the thickness of the compressible layer, and ground-water level. Controlling post-construction settlement for these types of structures is critical to prevent excessive differential settlement resulting in cracking of roadway pavements or visible movement of MSE wall facing panels.

Geopier Rammed Aggregate Pier® (RAP) soil reinforcing elements are installed prior to construction of MSE walls, embankment fills, and other transportation structures to reinforce and stiffen compressible foundation soils to reduce the magnitude and duration of settlement and control stability. The use of Geopier soil reinforcement to increase shear resistance and improve global stability is described in Technical Bulletin 5. Geopier elements used to reinforce matrix soils beneath an MSE wall and an embankment are illustrated in Figures 1a and 1b.

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2. GEOPIER CONSTRUCTION

Geopier RAP construction is described in detail in the Geopier Reference Manual (Fox and Cowell 1998) and in the literature (Lawton and Fox 1994, Lawton et al. 1994). The elements are constructed by drilling out a volume of compressible soil to create a cavity and then ramming select aggregate into the cavity in thin lifts using a patented beveled tamper. The ramming action causes the aggregate to compact vertically as well as to push laterally against the matrix soil, thereby increasing the horizontal stress in the matrix soil and reducing the compressibility of the matrix soil between the elements. Geopier RAP construction results in a very dense aggregate pier with a very high stiffness that yields a significantly increased composite stiffness within the Geopier-reinforced zone. The use of open-graded stone during construction affords radial drainage of excess pore water pressures to the elements, which act as vertical drains to increase the time-rate of settlement.

Figure 1a.
Geopier Soil Reinforcement
Support of MSE Wall

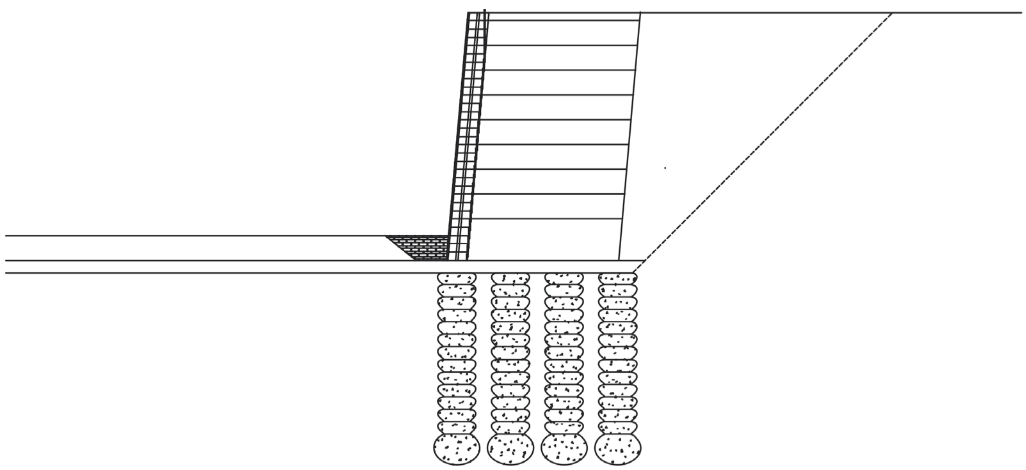
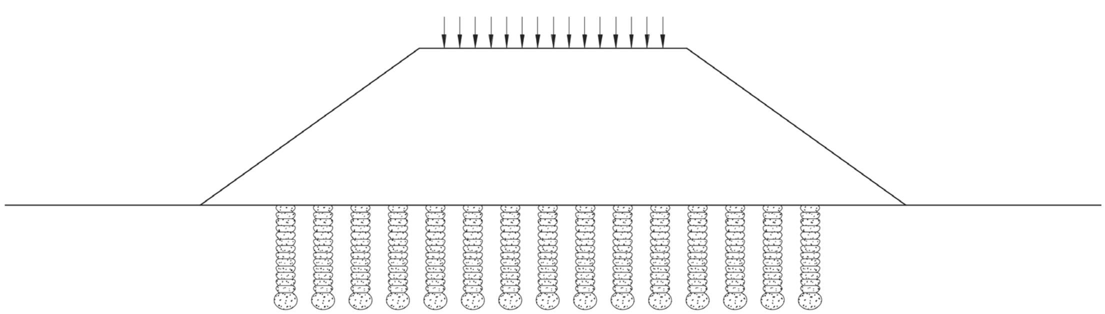


Figure 1b.
Geopier Soil Reinforcement
Support of Embankment



3. GEOPIER SETTLEMENT CONTROL DESIGN METHODOLOGY

The Geopier RAP soil reinforcement settlement control design methodology is based on a two-layer settlement approach as initially described by Lawton et al. (1994), Lawton and Fox (1994), and Wissmann et al. (2002). The installation of Geopier elements within the Geopier-reinforced zone, referred to as the upper zone, creates a stiffened, engineered zone with reduced compressibility that reduces settlement of embankments and transportation related structures. The settlement below the Geopier reinforced zone, referred to as the lower-zone, is evaluated using conventional geotechnical analysis approaches. The total settlement (S_{tot}) of the transportation structures is evaluated as the sum of the upper zone settlement (S_{uz}) and the lower zone settlement (S_{LZ}):

$$S_{tot} = S_{uz} + S_{LZ} . \qquad \text{Eq. 1.}$$

3.1 SETTLEMENT IN THE GEOPIER REINFORCED ZONE

Settlement in the Geopier-reinforced zone (upper zone) is estimated with Hooke's law:

$$S_{uz} = \frac{\Delta q \cdot I_\sigma \cdot H_{uz}}{E_{comp}} , \qquad \text{Eq. 2.}$$

where Δq is the embankment or wall bearing pressure, I_σ is the average stress influence factor in the upper zone (typically assumed to be 1.0), H_{uz} is the thickness of the reinforced upper zone layer, and E_{comp} is the composite elastic modulus of the reinforced upper zone layer. Values for E_{comp} are computed as the weighted average of the elastic modulus of the Geopier RAP elements (E_g) and the upper zone matrix soil elastic modulus (E_m):

$$E_{comp} = E_g \cdot R_a + E_m \cdot (1\text{-}R_a) , \qquad \text{Eq. 3.}$$

where R_a is the area replacement ratio.

Selected values for E_g depend on both the intrinsic elastic modulus of the constructed pier and on the ability of the foundation to apply concentrated stress to the tops of the piers. For rigid concrete foundations, full values of E_g may be used because the stress concentration ratio is equivalent to the pier/soil stiffness ratio. Smaller values of E_g are selected for soil embankments and flexible walls that cannot apply concentrated stresses as efficiently and thus cannot make full use of the pier stiffness values.

The upper zone settlement methodology provides for a determination of the deflection of the Geopier RAP, but not of the matrix soil between the piers. Field instrumentation results, however, show that only minor differential settlement is observed between the top of the Geopier RAP element and the matrix soil under embankment loading (Minks 2001, White 2002). More rigorous analyses may be used to evaluate the potential for differential settlement between the rammed aggregate piers and the matrix soil. However, the impacts on surficial settlement caused by differential settlement between the piers and matrix soil are minor when considering large embankment heights. This is related to the development of a plane of equal settlement caused by soil arching of the embankment material to the stiff Geopier RAP elements (Terzaghi 1936).

3.1 SETTLEMENT BELOW THE GEOPIER REINFORCED ZONE

Settlement below the Geopier-reinforced zone is evaluated using conventional geotechnical approaches, consisting of either elastic settlement analyses or consolidation analyses using the familiar expressions:

$$S_{LZ} = \frac{\Delta q I_\sigma H_{LZ}}{E} , \qquad \text{Eq. 4.}$$

and

$$S_{LZ} = c_c \left[\frac{1}{1+e_0}\right] H_{LZ} \log\left[\frac{P_0 + \Delta q}{P_0}\right] \qquad \text{Eq. 5.}$$

where H_{LZ} is the thickness of the compressible lower zone, E is the matrix soil elastic modulus within the lower zone, c_c is the matrix soil coefficient of compressibility, e_o is the matrix soil void ratio, P_o is the vertical effective stress at the mid-point of the compressible layer, and Δq is the average bearing pressure applied by the wall and embankment. The average applied bearing pressure is the product of the applied pressure and the stress influence factor, I_σ. The stress influence factor within the lower zone is typically assumed to be 1.0 because of the large lateral extent of MSE walls and embankment fills.

Typically, elastic modulus settlement approaches are used to estimate settlement in granular soils and heavily over-consolidated cohesive soils. Matrix soil equivalent elastic modulus values may be estimated using published correlations from SPT N-values, undrained shear strengths, CPT tip resistances, or other insitu tests. Consolidation settlement approaches are used to evaluate settlement in normally-consolidated or lightly over-consolidated cohesive soils.

4. TIME-RATE OF SETTLEMENT

The magnitude of post-construction settlement is often as important as the overall settlement of the MSE wall or embankment. Post-construction settlement may be dramatically reduced by using Geopier soil reinforcing elements constructed with open-graded stone to act as vertical drains, allowing radial drainage to occur to the elements. Radial drainage calculations can be performed to evaluate the percentage of excess pore water pressure dissipation that occurs within the estimated construction period and to determine the remaining post-construction settlement.

4.1 TIME-RATE OF SETTLEMENT IN THE GEOPIER REINFORCED ZONE

Radial drainage to the Geopier element is calculated using Barron's approach for estimating the settlement duration (t) from radial drainage to sand drains (1948). The approach relates the settlement duration to a time factor (T), the radial coefficient of consolidation (c_r), and the square of the effective drainage length (d_e):

$$t = \frac{T_r d_e^2}{c_r} \quad . \qquad \text{Eq. 6.}$$

The time factor is calculated by first evaluating the diameter ratio (n), which is the ratio of the effective drain diameter and the constructed diameter of the installed drain (d_w). Effective drain diameters are evaluated based on geometry for elements spaced in triangular grids and square grids, respectively:

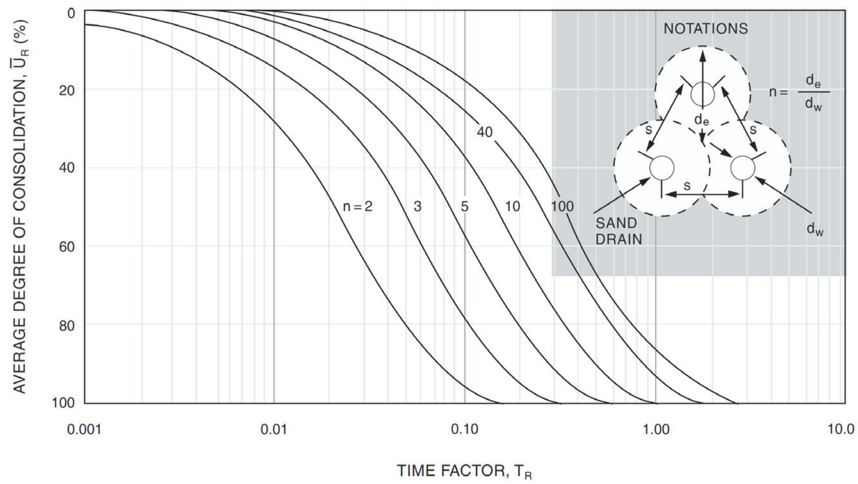
$$\text{Triangular grid: } d_e = 1.05s \,, \qquad \text{Eq. 7a.}$$

$$\text{Square grid: } d_e = 1.13s \,, \qquad \text{Eq. 7b.}$$

where s is the center-to-center spacing of the elements. The spacing of elements is selected to provide a sufficient increase in the upper zone stiffness to achieve tolerable post-construction settlement magnitudes (as described in Section 3), considering that a significant percentage of the settlement will occur during the construction period as a result of radial drainage.

The value of the radial coefficient of consolidation is commonly assumed to be between two and four times the vertical coefficient of consolidation value (c_v). This ratio may be significantly higher in varved or horizontally stratified soils. Coefficient of consolidation values (c_v) are related to many factors including soil mineralogy, gradation, and depositional history of the matrix soil (Terzaghi et al. 1996). For cohesive soils, these values are evaluated from consolidation tests or may be estimated from liquid limit values and stress history (over-consolidation).

Figure 2.
Degree of Consolidation for Radical Drainage Applications
(NAVFAC 1982)



Based on the diameter ratio (n) and the desired percentage of excess pore water pressure dissipation (μ), a time factor value can be interpreted from Figure 2.

The time factor (T_R) is then used in conjunction with the drainage path length (d_e) and the radial coefficient of consolidation value (c_r) to estimate the time of drainage (t) from Equation 6.

Recent research performed by Han and Ye (2001) describes a modified radial drainage approach that accounts for stress concentration to stiff aggregate columns. Stress concentration to the stiff Geopier elements reduces the amount of stress on the matrix soil, which causes settlement to occur faster and yields a modified (increased) radial coefficient of consolidation. Han and Ye suggest that a modified radial coefficient of consolidation be used in the Barron approach:

$$c'_r = c_r \left[1 + n_s \left[\frac{1}{n^2 - 1} \right] \right] , \quad \text{Eq. 8.}$$

where n_s is the stress concentration ratio. The modified radial coefficient of consolidation is substituted for the radial coefficient of consolidation in Equation 6 to determine the percentage of excess pore water pressure dissipation for a given time period.

Research has shown that Geopier stress concentration ratios for footing support range from 4 to 45 (Lawton and Merry 2000, Hoevelkamp 2002). Conservative values of stress concentration are suggested for design. This approach to evaluate radial drainage periods is supported by settlement monitoring results with time (Hoevelkamp 2002).

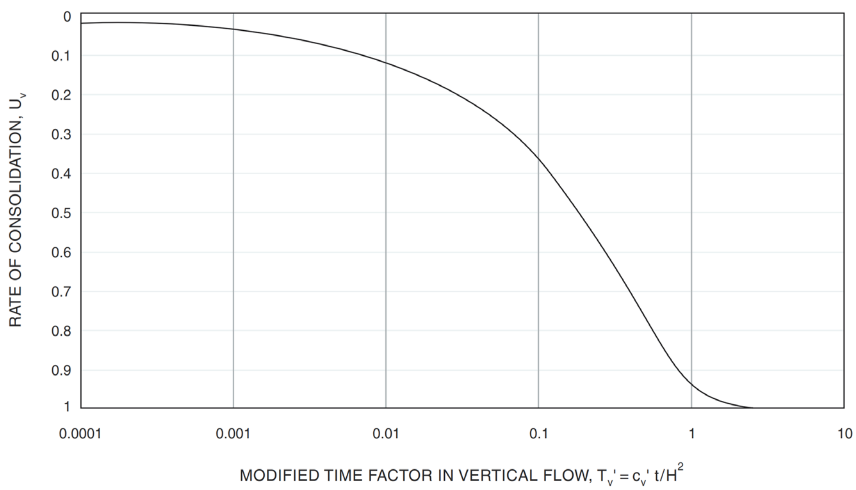
4.2 TIME-RATE OF SETTLEMENT BELOW THE GEOPIER REINFORCED ZONE

The time-rate of settlement below the Geopier reinforced zone is calculated using traditional expressions for vertical consolidation as shown in the following equation and described in the literature:

$$t = \frac{T_v (H_{dr})^2}{c_v} , \quad \text{Eq. 9.}$$

where t is drainage time c_v is the vertical coefficient of consolidation, H_{dr} is the vertical drainage path length, and T_v is the vertical time factor corresponding to a particular percentage of excess pore water pressure dissipation as determined from Figure 3.

Figure 3.
Degree of Consolidation for Vertical Drainage
(Han and Ye 2001)

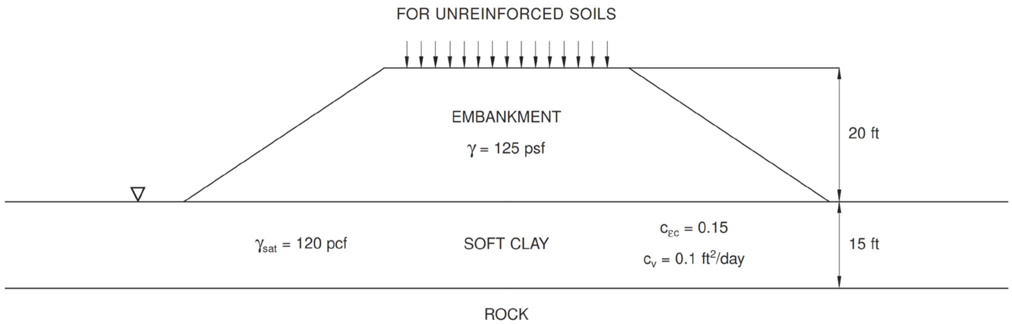


5. SETTLEMENT MAGNITUDE AND TIME-RELATED EXAMPLE

Example calculations performed for the placement of a 20-foot tall embankment constructed on a 15 foot thick layer of soft clay underlain by bedrock are presented in Figures 4 and 5. Figure 4 provides an example of conventional settlement magnitude and duration calculations for the embankment. Figure 5 illustrates the settlement magnitude and duration calculations for foundation soils reinforced with Geopier soil reinforcement as described above. Lower zone settlements are assumed to be negligible in both examples because the piers extend to rock.

The results of the example calculations shown in Figures 4 and 5 illustrate how the installation of Geopier soil reinforcement significantly reduces the settlement magnitude. Additionally, the settlement occurs at an increased rate resulting in the majority of the settlement taking place during construction.

Figure 4.
Settlement Magnitude and Duration Example
Calculation for Unreinforced Soils



SETTLEMENT MAGNITUDE

$$P_o = z(\gamma_{sat} - \gamma_w) = 7.5\text{ ft}(120\text{ pcf} - 62.4\text{ pcf}) = 432\text{ psf}$$

$$q = \gamma H = 125\text{ pcf }(20\text{ ft}) = 2{,}500\text{ psf}$$

$$I_\sigma = 1.0\text{ (for areal loads)}$$

$$E_m = \frac{(I_\sigma q)}{c_\varepsilon \log\left[\frac{P_o + I_\sigma q}{P_o}\right]} = \frac{(1.0)(2{,}500\text{ psf})}{0.15 \log\left[\frac{432 + 2500}{432}\right]} = 20\text{ ksf}$$

$$s_{unreinforced} = \frac{I_\sigma qH}{E_m} = \frac{(1.0)(2.5\text{ ksf})(15\text{ ft})}{20\text{ ksf}} = 1.875\text{ ft} = 22.5\text{ in}$$

TIME RATE OF SETTLEMENT (FOR 90% EXCESS PORE WATER PRESSURE DISSIPATION)

$$t_{90\%} = \frac{T_{90}(H_{dr})^2}{c_v} = \frac{0.848(7.5\text{ ft})^2}{0.1\text{ ft}^2/\text{day}} = 480\text{ days}$$

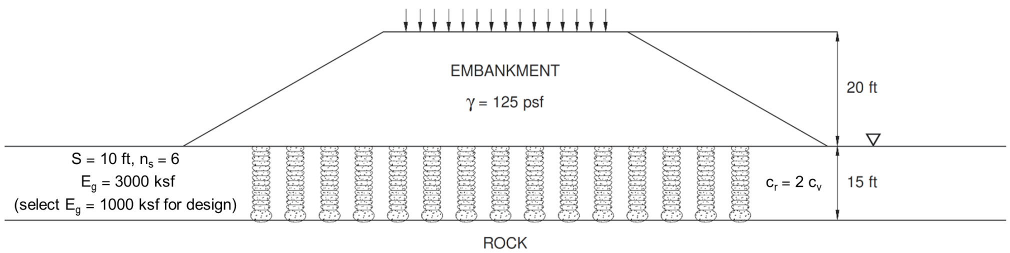
POST-CONSTRUCTION SETTLEMENT (AFTER 90 DAY PERIOD)

$$T_{90\text{ days}} = \frac{tc_v}{(H_{dr})^2} = \frac{90\text{ days}(0.1\text{ ft}^2/\text{day})}{(7.5\text{ ft})^2} = 0.16$$

At T = 0.16, U% is equal to 45% from Figure 3
Remaining settlement after 90 days is (1-U%)s = (1-0.45)(22.5 inches) = 12.4 inches

Figure 5.
Settlement Magnitude and Duration Example
Calculation for Geopier Reinforced Soils

FOR GEOPIER-REINFORCED SOILS
WITH AN ASSUMED STRESS CONCENTRATION RATIO OF 6



SETTLEMENT MAGNITUDE

$$R_a = \frac{A_g}{A} = \frac{5.94 \text{ ft}^2}{(10 \text{ ft})^2} = 0.06$$

$$q = \gamma H = 125 \text{ pcf } (20 \text{ ft}) = 2.5 \text{ ksf}$$

$$E_{comp} = E_g R_a + E_m(1 - R_a) = 1000 \text{ ksf } (0.06) + 20 \text{ ksf } (1 – 0.06) = 78.8 \text{ ksf}$$

$$s_{uz} = \frac{I_\sigma q H_{uz}}{E_{comp}} = \frac{1.0 \text{ } (2.5 \text{ ksf}) \text{ } (15 \text{ ft})}{78.8 \text{ ksf}} = 0.476 \text{ ft} = 5.7 \text{ in}$$

TIME RATE OF SETTLEMENT (FOR 90% EXCESS PORE WATER PRESSURE DISSIPATION)

$$n = \frac{d_e}{d_w} = \frac{1.13s}{d_w} = \frac{1.13(10 \text{ ft})}{2.75 \text{ ft}} = 4.1$$

$$c'_r = c_r \left[1 + n_s \frac{1}{n^2 - 1} \right] = 0.2 \text{ ft}^2 / \text{day} \left[1 + 6 \frac{1}{(4.1)^2 - 1} \right] = 0.28 \text{ ft}^2 / \text{day}$$

POST-CONSTRUCTION SETTLEMENT (AFTER 90 DAY PERIOD)

$$T = \frac{t_{90 \text{ days}} c'_r}{(d_e)^2} = \frac{90 \text{ days}(0.28 \text{ ft}^2 / \text{day})}{(11.3 \text{ ft})^2} = 0.20$$

For a time factor (T) = 0.20, N = 4.1, U% is equal to 90% from Figure 2
Remaining settlement after 90 days is (1-U%)s = (1-0.90)(5.7 inches) = 0.6 inches

6. SUMMARY

Geopier soil reinforcement is used to reinforce and stiffen compressible foundation soils and increase the time-rate of settlement in order to control post-construction settlement magnitudes. The design methodology utilizes conventional settlement and radial drainage approaches with minor modifications based on advanced research to determine the Geopier element spacing required to control settlement and meet project settlement criteria.

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SYMBOLS USED

c_c	=	Matrix soil coefficient of compressibility
c_r	=	Radial coefficient of consolidation
c'_r	=	Modified radial coefficient of consolidation
c_v	=	Vertical coefficient of consolidation
d_e	=	Drainage path length
e_o	=	Matrix soil void ratio
E	=	Matrix soil elastic modulus within the lower zone
E_{comp}	=	Composite elastic modulus of the reinforced upper zone layer
E_g	=	Elastic modulus of the Geopier element
E_m	=	Upper zone matrix soil elastic modulus
H_{dr}	=	Vertical drainage path length
H_{uz}	=	Thickness of the reinforced upper zone layer
H_{LZ}	=	Thickness of the compressible lower zone layer
I_σ	=	Average stress influence factor in the upper zone
n	=	Diameter ratio
P_o	=	Veritcal Effetive Stress at the mid-point of the compressible layer
Δq	=	Average bearing pressure applied by the embankment or wall
R_a	=	Ratio of the area coverage of the Geopier elements to the gross area of the soil matrix
S_{tot}	=	Total settlement of the structure
S_{uz}	=	Settlement of the upper zone
S_{LZ}	=	Settlement of the lower zone
T_r	=	Radial time factor
T_v	=	Vertical time factor
t	=	Settlement duration

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