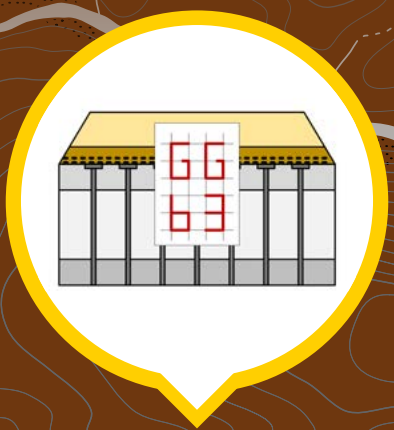
Geotechnical Special Publication No. 356

Theory Manual for the Load Displacement Compatibility Method (LDC) for Design of Column-Supported Embankments

A Companion to GeogridBridge 3.0



Michael P. McGuire, Ph.D., P.E.
Eric M. Hunstein
Elise G. Hummel
Joel A. Sloan, Ph.D., P.E.

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Sponsored by the
Geosynthetics Technical Committee of the
Technical Coordination Council of the Geo-Institute of the
American Society of Civil Engineers

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Contents

Contributors vii

Acknowledgments ix

Preface xi

Notation xiii

Chapter 1 Introduction 1
References 3

Chapter 2 Load Transfer Mechanisms 5
2.1 Soil Arching 8
2.1.1 Incremental Arching Derivation 9
2.1.2 Arching Mobilization 12
2.2 Load Transfer through Tensioned Geosynthetic 16
2.2.1 Overview of the Parabolic Method 16
2.2.2 Derivation of the Parabolic Method 17
2.3 Drag force 25
References 26

Chapter 3 Consolidation and Compression 29
3.1 Initial and Final Stresses 29
3.2 Clays 30
3.2.1 Ultimate Consolidation Strain 30
3.2.2 Time Rate of Consolidation 30
3.3 Sands 32
3.4 Column and Pile Cap 32
References 33

Chapter 4 Monte Carlo Simulation 35
4.1 Introduction 35
4.2 Example of a Geotechnical Application of a Monte Carlo Simulation 36
References 38

Index 39

Contributors

Michael P. McGuire, *Associate Professor*, Lafayette College, Dept. of Civil and Environmental Engineering

Eric M. Hunstein, *Graduate Student*, Virginia Tech, Dept. of Civil and Environmental Engineering

Elise G. Hummel, *Graduate Student*, Virginia Tech, Dept. of Civil and Environmental Engineering

Joel A. Sloan, *Professor*, US Air Force Academy, Dept. of Civil and Environmental Engineering

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Preface

This book provides detailed information on the theory, assumptions, and mathematical execution of the load displacement compatibility (LDC) method for design of column-supported embankments (CSEs) with respect to settlement and mobilization of geosynthetic reinforcement for vertical load transfer. The Theory Manual and the companion resources listed following provide information and tools related to the design and construction of CSEs:

- *Theory Manual for the Load Displacement Compatibility Method (LDC) for Design of Column-Supported Embankments*, GSP 356: This manual provides comprehensive technical information about the LDC method for design of column-supported embankments. Users of the GGB3 spreadsheet should be familiar with the content in the theory manual prior to using the spreadsheet for design. This manual, which is this current book, is available as GSP 356 through the ASCE Library.
- Geotechtools.org: This website, which is free to access, provides practical information about column-supported embankments and many other geotechnologies. The information on column-supported embankments provides an excellent primer on the technology and the state of the US practice. The content is periodically updated to reflect advancements in design and construction.
- GeogridBridge 3.0 (GGB3) spreadsheet: This spreadsheet implements the LDC method as described in the LDC theory manual. The spreadsheet is available on geotechtools.org.
- *User's Manual for GeogridBridge 3.0: A Guide to the Load Displacement Compatibility Method (LDC) for Design of Column-Supported Embankments*: This manual provides information on the use of the GGB3 spreadsheet and provides two worked examples.

The original LDC method and GeogridBridge 3.0 spreadsheet were developed by Dr. George Filz and Dr. Miriam Smith. The LDC method was first documented in a report submitted to the Virginia Transportation Research Council (Filz and Smith 2006). The method was revised as part of the Strategic Highway Research Program (SHRP) 2 project and was documented by Schaefer et al. (2017). The authors appreciate the hard work and creativity that went into these efforts.

The Theory Manual and GGB3 spreadsheet reflect the latest version of the LDC method which allows for greater flexibility compared to earlier versions with respect to defining embankment and subsurface stratigraphy, column arrangement, characterization and mobilization of vertical load transfer

mechanisms, soil stress history and compressibility, as well as consideration of parameter uncertainty.

The Geosynthetics Technical Committee provided a detailed review of this manual. The suggested revisions stemming from this review have been incorporated into the final version. The authors acknowledge and appreciate the contributions of the committee in making this manual a reality.

Finally, the authors appreciate the support of Lafayette College and the US Air Force Academy during the development of the Theory Manual and GGB3 spreadsheet. This effort was also supported, in part, by a Special Project endorsed by the Geosynthetics Technical Committee and overseen by the Board of Governors of the Geo-Institute of ASCE. The authors also appreciate the support of the Collin Group to make updates to CSE content on geotechtools.org.

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Notation

A	Unit cell area
A_c	Area of column in a unit cell; the cross-sectional area of the column or cap
$A_{\text{rectangular}}$	Unit cell area in a rectangular array
A_s	Portion of the unit cell area occupied by soil at the elevation of the reinforcement
A_{s1}	Tributary area of unit cells along span c_1
A_{s2}	Tributary area of unit cells along span c_2
$A_{\text{triangular}}$	Unit cell area in a triangular array
a	Equivalent square width of the column or pile cap
a_s	Area replacement ratio; the ratio of the area of column in a unit cell, A_c, to the unit cell area, A
AR	Arching ratio used in the concentric arches and Hewlett and Randolph models
AVG, $\overline{x}$	Average parameter value
B	Ratio of the area of soil in a unit cell to the perimeter of the column
BAT	Bilinear adapted Terzaghi method for modeling arching mobilization
c	The total cohesion or adhesion
c'	Effective cohesion
c_1, c_2	Clear spans used in the parabolic method, over which the vertical load is uniformly distributed; $c_1 \leq c_2$
c_1, c_2, c_3, c_4, c_5, c_6, c_7	Coefficients used to predict the arching ratio
$C_{\varepsilon c}$	Compression ratio; the slope of the rebound portion of the consolidation curve on a log-stress versus strain diagram
$C_{\varepsilon r}$	Recompression ratio; the slope of the virgin portion of the consolidation curve on a log-stress versus strain diagram
c_v	Coefficient of consolidation
CA	Concentric arches model
COV	Coefficient of variation
d, d_c	Column diameter
d_{cap}	Pile cap diameter
$DS_{b,d}$	Largest differential settlement at the base of the embankment
$DS_{b,d,\text{yield}}$	Displacement at which arching becomes fully mobilized
d_w	Depth below the base of the embankment to the groundwater table

dz	Vertical thickness of an increment used in the incremental form of the adapted Terzaghi (AT) method
d_1	Maximum deflection of the reinforcement across the c_1 span
d_2	Maximum deflection of the reinforcement across the c_2 span
$d\sigma'_z$	Effective pressure of the increment used in the incremental form of the adapted Terzaghi (AT) method
E	Value of efficacy used in the calculation of the SRR according to the HR model
E_a	Young's modulus of the arching soil
E_c	Young's modulus of the column and pile cap
E_s	Young's modulus of the sand layer
$F_r(T)$	Infinite series used in calculating the Janbu degree of consolidation, U_r
f'_c	Compressive strength of concrete
f_s	Shape factor for the strain distribution used in time rate of consolidation calculations
GGB	GeogridBridge
GRC	Ground reaction curve
H, H_{emb}	Total embankment height
H_a	Height of arching used in the incremental form of the adapted Terzaghi method
H_{cap}	Height of the pile cap
H_{col}	Length of the column
H_{crit}	Critical height of the embankment; the minimum embankment height at which differential settlement at the base of the embankment will not produce differential settlement at the surface of the embankment
H_{dr}	Maximum drainage path
H_q	Height above arching used in the incremental form of the adapted Terzaghi method
HR	Hewlett and Randolph model
i	Reference to the current increment used in the incremental form of the adapted Terzaghi (AT) method
J	Combined long term tensile stiffness of the geosynthetic across each span between columns
J_1	Tensile stiffness of the geosynthetic along the c_1 span
J_2	Tensile stiffness of the geosynthetic along the c_2 span
K	Lateral earth pressure coefficient for evaluating load transfer by soil arching or drag force
K_{o}	At-rest earth pressure coefficient
K_p	Rankine passive earth pressure coefficient
k	Coefficient relating $DS_{b,d}$ to the average of the midspan deflections, generally equal to 1
k_1	Coefficient for span c_1 used in the parabolic method

k_2	Coefficient for span c_2 used in the parabolic method
LB	Lower bound of a distribution used in an MCS
LDC	Load displacement compatibility
LTP	Load transfer platform
LTM	Load transfer mat
M_c	One-dimensional elastic compression modulus of the column and pile cap
M_s	One-dimensional elastic compression modulus of the sand
MCS	Monte Carlo Simulation
m	Slope of the deflected shape of the reinforcement
N	Number of trials to be run in an MCS
n	Total number of increments used in the incremental form of the adapted Terzaghi (AT) method
OCM	Overconsolidation margin
OCR	Overconsolidation ratio
P_a	Atmospheric pressure
P_{exceed}	Probability of serviceability failure
P'_{bottom}	Effective normal force acting upward on the bottom of the increment used in the incremental form of the adapted Terzaghi (AT) method
P'_{top}	Effective force acting on top of an increment because of overburden used in the incremental form of the adapted Terzaghi (AT) method
p	Perimeter of the column or pile cap
P	Preload during construction
q	Postconstruction surface loading
$RF_{CR,5\%}$	Reduction factor for creep at 5% strain
$RF_{CR,ult}$	Reduction factor for creep at the ultimate strain
RF_D	Reduction factor for durability
RF_{ID}	Reduction factor for installation damage
r	Coefficient that alters the shape of the strain profile used in the time rate of consolidation calculations
$S_{b,c}$	Settlement at the base of the embankment directly over the column
$S_{b,d}$	Settlement at the base of the embankment at a distance s' from the edge of the nearest column or pile cap
S_c	Settlement at the embankment surface directly over the column
S_d	Settlement at the embankment surface at a distance s' from the edge of the nearest column or pile cap
S_s	Total uniform settlement at the embankment surface
$S_{s,pc}$	Total postconstruction settlement at the embankment surface
S_u	Undrained strength
SD, σ	Standard deviation

SGRC	Simplified ground reaction curve
SGRC-ACA	Simplified ground reaction curve estimated using the approximate concentric arches model
SGRC-AHR	Simplified ground reaction curve estimated using the approximate Hewlett and Randolph model
SRR	Stress reduction ratio
SRR_{emb}	Stress reduction ratio associated with load transfer by arching within the embankment
SRR_{fndn}	Stress reduction ratio associated with load transfer by arching within the embankment and tension developed in the geosynthetic
SRR_{peak}	Value of SRR_{emb} at peak arching
SRR_{term}	Value of SRR_{emb} at terminal arching
s'	Greatest distance a location within the unit cell can be from the edge of the closest column, as represented using a circular cross section
s_1, s_2	Center-to-center spacing between the columns. $s_1 \leq s_2$
T_v	Dimensionless time factor used in the time rate of consolidation calculations
T	Tension in the geosynthetic reinforcement
T_1	Tension developed within the reinforcement across the c_1 span per unit width
T_2	Tension developed within the reinforcement across the c_2 span per unit width
$T_{x,1}$	Horizontal component of T_1
$T_{x,2}$	Horizontal component of T_2
$T_{z,1}$	Vertical component of T_1
$T_{z,2}$	Vertical component of T_2
$T_{5\%,LT}$	Long-term tensile strength at 5% strain
$T_{5\%,ST}$	Short-term tensile strength at 5% strain
t	Time available for consolidation prior to post-construction surface loading
U_r	Janbu degree of consolidation
U_0	Terzaghi degree of consolidation
UB	Upper bound of a distribution used in an MCS
UGRC	User-defined ground reaction curve
V	Vertical shear force between moving and fixed portions of the increment used in the incremental form of the adapted Terzaghi (AT) method
W'	Effective weight of the increment used in the incremental form of the Adapted Terzaghi (AT) method
w_1	Magnitude of the uniform vertical line load across the c_1 span
w_2	Magnitude of the uniform vertical line load across the c_2 span

z_{np}	Depth below the embankment surface to the neutral plane
α	Factor used to scale undrained strength to soil-column adhesion in α-Method
γ	Material unit weight
γ_{total}	Total unit weight
γ'	Effective unit weight
γ_{water}	Unit weight of water
δ	Interface friction angle
$\Delta\sigma_z$	Change in total stress in compressible layer owing to excavation or filling
ε_s	Strain at the top of the clay layer
ε_d	Difference between the strain at the top and the bottom of the clay layer
$\varepsilon_{s,\text{ult}}$	Ultimate strain in a sand increment
ε_1	Average strain in the geosynthetic reinforcement along span c_1
ε_2	Average strain in the geosynthetic reinforcement along span c_2
ν_a	Poisson's ratio of the arching soil
ν_c	Poisson's ratio of the column and pile cap
ν_s	Poisson's ratio of the sand layer
σ'_c	Vertical stress in the column
$\sigma_{\text{col,geobot}}$	Stress acting on the columns owing to the embankment load considering both soil arching and the tensioned geosynthetic (if present) for load transfer
$\sigma_{\text{col,geotop}}$	Stress acting on the columns owing to the embankment load considering exclusively load transfer through soil arching
σ_{net}	Average net vertical pressure carried by the reinforcement
σ'_o	Initial vertical effective stress in the foundation soils based on the effective overburden stress prior to loading from the embankment or surface loading and including any stress adjustment
σ'_p	Preconsolidation stress
σ'_s	Final vertical effective stress in the soil after embankment construction and application of surface considering the effects of vertical load transfer
$\sigma'_{s,i}$	Vertical stress at the base of each foundation soil increment above the neutral plane
$\sigma_{\text{soil,geobot}}$	Stress acting on the foundation soil owing to the embankment load considering both soil arching and the tensioned geosynthetic (if present) for load transfer
$\sigma_{\text{soil,geotop}}$	Stress acting on the foundation soil owing to the embankment load considering exclusively load transfer through soil arching

$\sigma'_{z,a}$	Vertical effective stress calculated after embankment construction without considering any load transfer to the columns; equivalent to the average vertical stress within the unit cell with load transfer to the columns
$\sigma'_{z,\text{adjust}}$	Adjustment to the effective vertical stress based on the profile before embankment and surface loading to obtain the initial vertical effective stress
$\sigma'_{z,b}$	Effective vertical stress in the soil based on the profile before the loading from the embankment and surface loading and without any stress adjustment
$\sigma'_{z,\text{base}}$	Vertical effective stress imposed on the base of the embankment without considering load transfer
ϕ'	Effective internal friction angle

CHAPTER 1
Introduction

Column-supported embankments (CSEs) are a method of ground improvement commonly used when an embankment is required over soft, compressive soil that is likely to experience large settlements because of the added load in the absence of soil improvement. A typical cross section of a CSE can be seen in Figure 1-1. In a CSE, load is transferred from the soil to the surrounding columns, significantly reducing the load felt by the soil and thereby reducing settlement. Column-supported embankments are an alternative to other methods to mitigate settlement in compressible soils, such as the use of prefabricated vertical drains (PVDs) and surcharge fills. Despite the effects that PVDs and surcharge fills have on the time rate of consolidation, these methods still require some time to reduce postconstruction settlement to an acceptable magnitude, and they do not directly address issues with large total settlements such as damage to nearby facilities. Because a CSE can greatly reduce the ultimate consolidation settlement, the embankment can be constructed immediately and there is less potential for damage to nearby facilities.

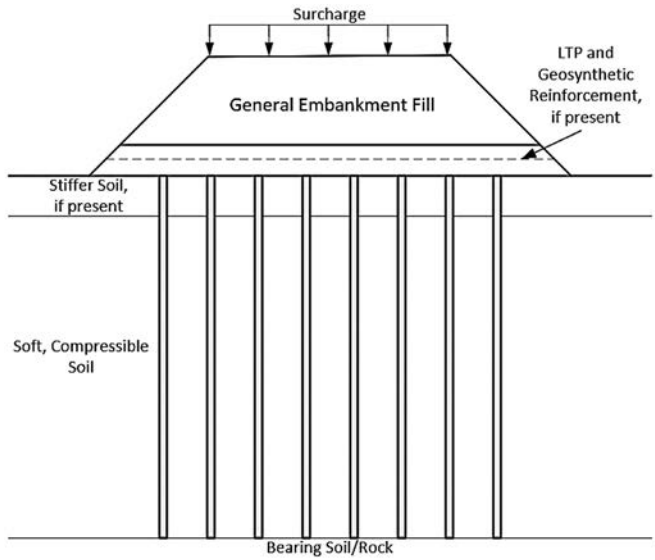


Figure 1-1. Typical CSE cross section.

Column-supported embankments are most often constructed with either a square, rectangular, or triangular column arrangement. Figure 1-2 depicts the plan view of the unit cells for each array. The center-to-center spacings between columns are denoted as s_1 and s_2. The term s' is defined as the greatest distance a location within the unit cell can be from the edge of the closest column, as represented using a circular cross section. The area replacement ratio, a_s, for a given unit cell is defined as the ratio of the area of column in a unit cell, A_c, to the unit cell area, A. There is always one column per unit cell, so A_c is equal to the cross-sectional area of the column or cap, if present. A pile cap may be included to aid in load transfer by increasing A_c. Equations (1-1) and (1-2) calculate the unit cell area, A, for rectangular and triangular column arrays, respectively.

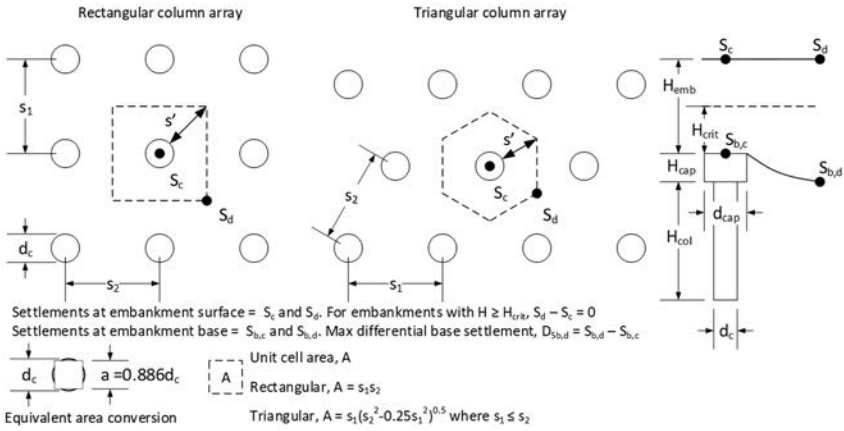


Figure 1-2. Unit cells for rectangular and triangular column arrays.

$$A_{\text{rectangular}} = s_1 s_2 \tag{1-1}$$

$$A_{\text{triangular}} = s_1\sqrt{s_2^2 - 0.25s_1^2} \tag{1-2}$$

For triangular column arrangements, $s_2 \geq s_1$.

Figure 1-2 also defines key locations of settlement at the top and base of the embankment, specifically over the column, S_c, and at a distance s' from the edge of the nearest column or pile cap, S_d. Settlements at the base of the embankment are distinguished from settlements at the top of the embankment using a "b" subscript, for example, $S_{b,d}$. The largest differential settlement at the base of the embankment occurs between the locations in the unit cell that receive the most and least vertical support from the columns (i.e., $DS_{b,d} = S_{b,d} - S_{b,c}$).

Vertical load transfer to the columns requires differential settlement between the columns and the base of the embankment. If the embankment is too thin, the differential settlement at the base will result in differential settlement at the surface, which is undesirable for providing good ride quality and pavement longevity. The critical height, H_{crit}, of a column-supported embankment is

defined as the minimum embankment height at which differential settlement at the base of the embankment will not produce differential settlement at the surface of the embankment. McGuire (2011) found that the critical height for a square arrangement of columns is largely a function of the column spacing and column diameter, as seen in Equation (1-3). In addition, the use of geosynthetic reinforcement was not found to significantly affect the critical height of an embankment. In general, CSEs should be designed and constructed with a total embankment height greater than the critical height.

$$H_{\text{crit}} = 1.15s' + 1.44d_c \tag{1-3}$$

Embankments with a total height at least as tall as the critical height are expected to experience uniform surface settlement, although there will be differential settlement at the base. Russell et al. (2003) proposed that the uniform settlement resulting from differential base settlement may be estimated assuming no volume change (i.e., dilation or contraction occurs within the embankment). Furthermore, they suggest that the average differential settlement at the base of the embankment is equal to half of the maximum deflection. Using the guidance by Russell et al. (2003), the surficial settlement for embankments with a total height greater than the critical height can be calculated with Equation (1-4). By interpreting experimental results by Sloan (2011) and Demerdash (1996), McGuire et al. (2015) noted that this equation often produces conservative results because the relatively dense embankment fill likely dilates because of shearing at the tops of columns or pile caps.

$$S_s = \frac{DS_{b,d}(1 - a_s)}{2} \tag{1-4}$$

where

S_s = Uniform settlement at the embankment surface,
$DS_{b,d}$ = Maximum differential settlement at the base of the embankment, and
a_s = Area replacement ratio.

The remainder of this manual describes the following:

- Three load transfer mechanisms in a CSE: soil arching, tensioned geosynthetic, and drag force, including derivations of the equations used in GeogridBridge 3.0;
- Consolidation of clays and compression of sands and columns; and
- Procedures for Monte Carlo simulations.

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Demerdash, M. A. 1996. "An experimental study of piled embankments incorporating geosynthetic basal reinforcement." *Ph.D. thesis*, University of Newcastle-Upon-Tyne, Dept. of Civil Engineering.