1998

Maximum Levee Height as a Function of Red River Valley Foundation Sediments

Lori Gunderson

MAXIMUM LEVEE HEIGHT AS A FUNCTION OF RED RIVER VALLEY FOUNDATION SEDIMENTS

by

Lori Gunderson

A Engineering Design

Submitted to the Department of Geology and Geological Engineering

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Bachelor of Science

Grand Forks, North Dakota
July
1998

TABLE OF CONTENTS

ABSTRACT

Grand Forks, North Dakota is located on glacio-lacustrine clays and other assorted sediments. This design project focuses on determining levee height safely supported in this geologic setting. Maximum levee height above the most unsuitable foundation materials was determined using two modifications of Terzaghi's Ultimate Bearing Capacity Equation. Allowable levee heights with desired construction safety factors are less than heights necessary to protect against a 1997 magnitude flood.

INTRODUCTION

Grand Forks, North Dakota is located in the Red River Valley, on glacio-lacustrine clays. This design investigates the capacity of these glacio-lacustrine clays to support a large levee system intended to provide flood protection for the city.

APPROACH

Soil characteristics and area stratigraphy, as described in detail in my design proposal, indicate levee height will be limited by subsurface strength. The capacity of foundation sediments to support a large levee system will be determined using the following approach:

- Review of area stratigraphy,
- Review of engineering characteristics
- Specification of USACE generic levee section attributes,
- Description of design assumptions,
- Introduction to bearing capacity,
- Explanation of Terzaghi's Ultimate Bearing Capacity Equation,
- Determination of maximum levee height,
- Estimation of construction cost per linear foot,
- Conclusions,
- Recommendations.

1.0 STRATIGRAPHY

Lacustrine deposition was the dominant geomorphic process resulting in Red River Valley sediments. The alluvium, Sherack, Brenna, and Falconer Formations comprise the four uppermost stratigraphic units beneath Grand Forks County.

The cross section utilized for maximum levee height calculation must be selected in accordance with the most unsuitable underlying materials (Terzaghi, 1967). The area surrounding the Kennedy Bridge on US Highway 2 is the most unsuitable zone for construction purposes (Figure 1) due to its high subsurface percentage of weak Brenna Formation sediment. The core drawn at this locality (Figure 2) denoted 94-17M, contains 9.3 feet of alluvium, 8.04 feet of Sherack Formation, 33.72 feet of Brenna Formation (25.38 foot Upper Brenna, 8.34 foot Lower Brenna,) and 5.94 feet of Falconer Formation, for a total surveyed section of 57 feet.

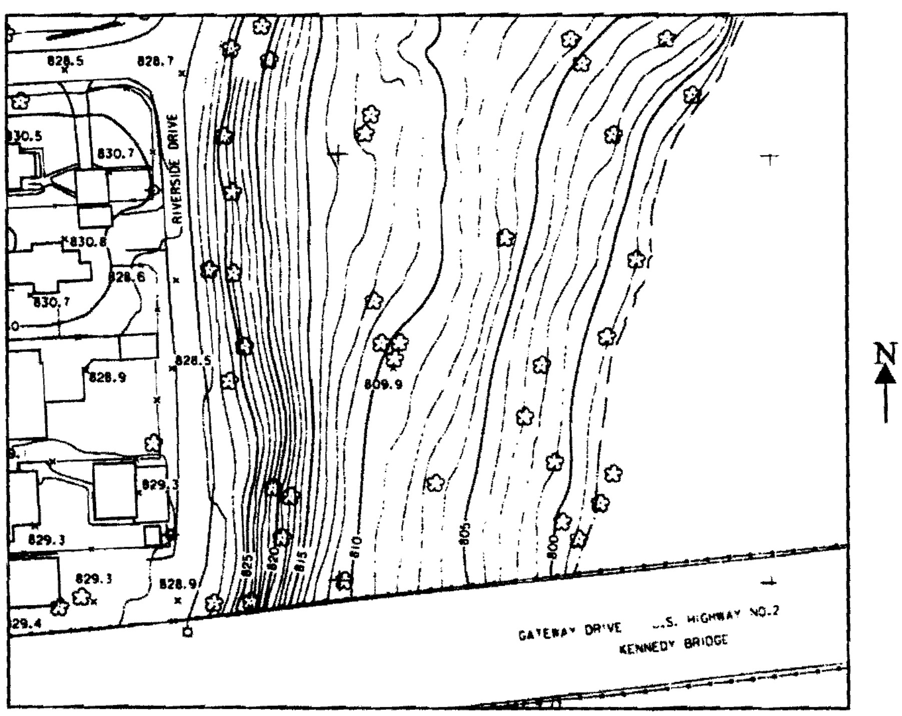


Figure 1. Topographic Area in Proximity of core sample 94-17M (as modified from City of Grand Forks, 1994).

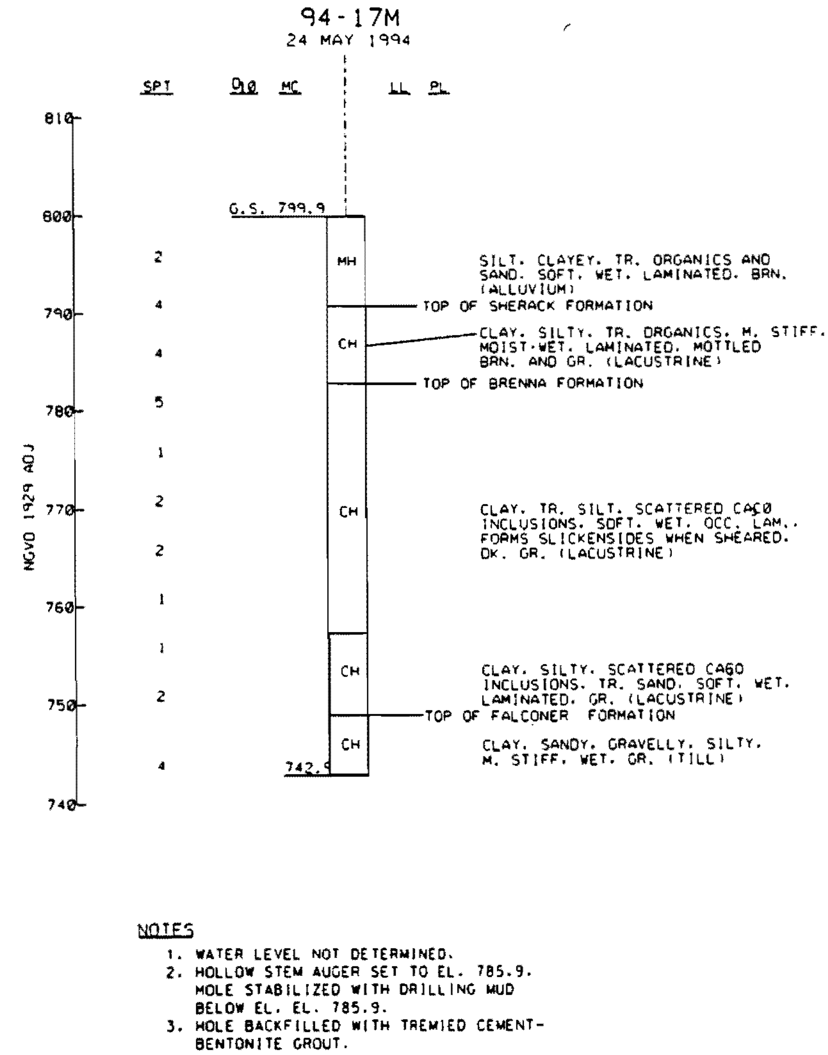


Figure 2. Stratigraphic Column (as modified from City of Grand Forks & USACE, 1995).

2.0 ENGINEERING CHARACTERISTICS

The following engineering characteristics govern maximum levee height: unit weight (γ), cohesion (c), and angle of internal friction (ϕ). Table 1 indicates the values of these characteristics by stratigraphic unit.

	γ (lb/ft^3)	c (lb/ft^2)	ϕ (degrees)
Alluvium	122	875	13
Sherack	122	875	13
Upper Brenna	100	350	4
Lower Brenna	110	375	7
Falconer	126	600	10

Table 1. Engineering Characteristics (City of Grand Forks & USACE, 1995).

3.0 GENERIC LEVEE SECTION

The USACE Engineering Manual (EM) 110-2-1913 entitled "Design and Construction of Levees," provides guidelines for the geometry of a generic levee cross section. Following these guidelines, levee side slope will be set at a value of 1 foot vertical on 2 foot horizontal (β = 27°). Crown width will be 10 feet, the minimum required for normal maintenance and flood fighting operations (Figure 3).

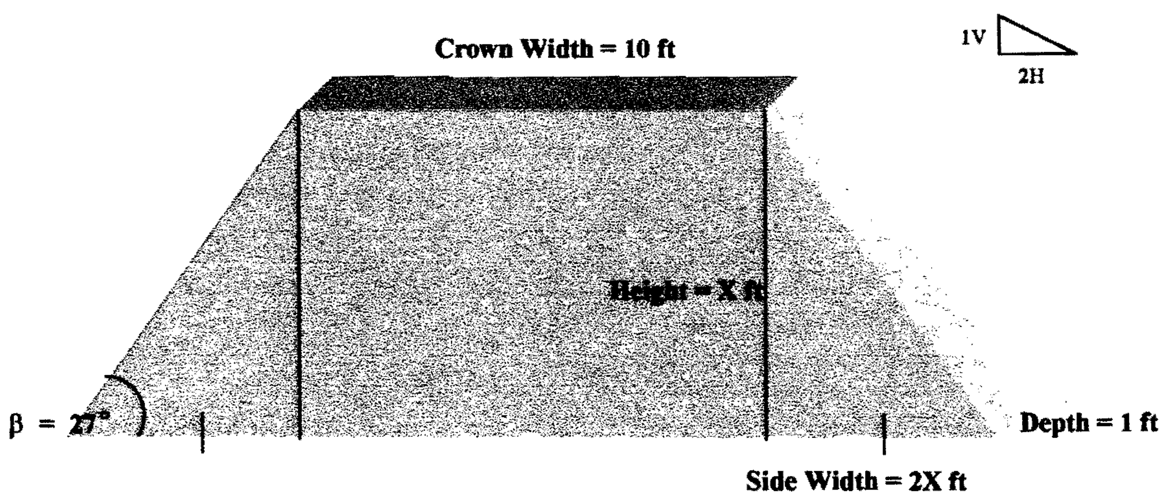


Figure 3. Generic Levee Section. (Not to scale).

Levee characteristics can be evaluated using the following relationships.

Volume (ft^3) per linear foot of the levee can be calculated using the formula for volume of a trapezoid:

$$V_{per\ levee\ foot} = levee_{height} * levee_{width} * levee_{depth} \quad \text{(eq. 3-1)}$$

where $levee_{height}$ = X feet
$levee_{width}$ = 2X + 10 feet
$levee_{depth}$ = 1 foot

The weight (lb) per linear foot of levee can be defined by multiplying the unit weight of the fill material by the volume per foot:

$$Wt_{per\ levee\ foot} = V_{per\ levee\ foot} * \gamma_{levee\ fill} \quad \text{(eq. 3-2)}$$

The pressure, or load per square foot (lb/ft^2) of levee is defined as the volume of the levee multiplied by the unit weight of the fill material divided by the levee footprint per linear foot of levee:

$$P_{per\ levee\ foot} = [V_{per\ levee\ foot} * \gamma_{levee\ fill}] / (\underline{total}\ levee\ width * 1\ ft\ depth) \quad \text{(eq. 3-3)}$$

where total levee width = 4X + 10 feet
(X = levee height)

4.0 DESIGN ASSUMPTIONS

The area stratigraphy, formation engineering characteristics, and generic levee cross section have been established. Specific design assumptions include:

- Levee will be constructed on a level surface (not on a slope), isolated from any underground defects (faults, cavities, mines, sewers, underground cables or utilities),
- Levee fill material properties are the same as those of the alluvial deposits and Sherack Formation because these units comprise the most likely borrow material (City of Grand Forks & USACE, 1998),
- Levee foundation is equivalent to a strip footing, depth = 0 (at ground surface),
- Levee load is uniformly distributed,
- Effects of groundwater are negligible,
- The minimum required constructed factor of safety is 2.0.

5.0 INTRODUCTION TO BEARING CAPACITY

Bearing capacity is the ability of underlying soil to carry a load without failure within that soil mass (Sowers, 1961). In this case, the load (q) imposed is from the levee itself (Figure 4). Load is a function of the volume and unit weight of the levee (eq. 3-3), which depends ultimately

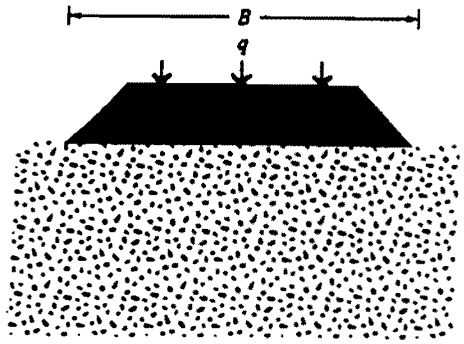


Figure 4. Model for Bearing Capacity, Structure Width = B (modified after Das, 1994).

on levee height. As height increases, overall dimensions of the levee increase, as does volume (eq. 3-1), weight (eq. 3-2), and load (eq. 3-3). At failure, the load exceeds the strength of the soil, and the structure will undergo a large settlement without any further load increase (Figure 5). As the foundation settles under the levee induced distributed load, a triangular zone of soil (zone I) is forced down, and presses zones II and III (Figure 5) sideways, and then upwards. At failure, the soil on the foundation sides will bulge out, and a slip zone will extend upwards towards the ground surface (Das, 1994).

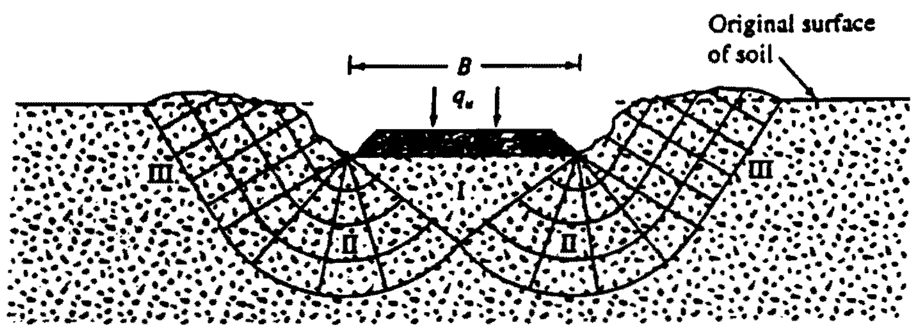


Figure 5. Failure by Load Exceeding Maximum Soil-Bearing Capacity (modified after Das, 1994).

The point at which bearing capacity failure will occur can be determined through several methodologies. Terzaghi's Ultimate Bearing Capacity Equation is used here.

6.0 TERZAGHI'S ULTIMATE BEARING CAPACITY EQUATION

Terzaghi's general equation for ultimate bearing capacity can be written as follows:

$$q_0 = [(1/2)*(\gamma*B*N_\gamma])] + [c*N_c] + [q*N_q] \text{ (Meyerhoff, p.4)} \qquad \text{(eq. 6-1)}$$

where q_0 = ultimate bearing capacity of soil (lb/ft^2)
γ = unit weight of soil (lb/ft^3)
B= width of applied load [levee width, (4X + 10)ft]
N_γ = factor showing the influence of soil weight and foundation width
c = cohesion (lb/ft^2)
N_c = factor showing the influence of cohesion
$q = \gamma*D_f = 0$, because D_f = depth of foundation = 0 ft (Das, p. 469)
N_q = factor showing the influence of the surcharge

The symbols N_γ, N_c, and N_q are bearing capacity factors which are functions of a soil's angle of internal friction (ϕ). These factors for different ϕ values are shown in Figure 6.

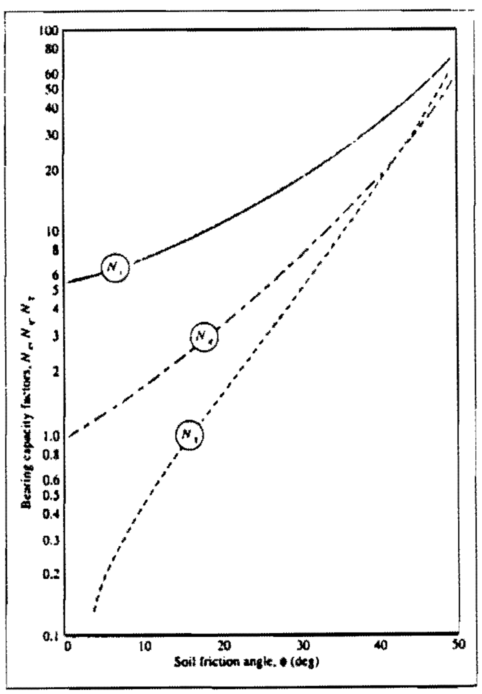


Figure 6. Bearing Capacity Factors for Strip Footings (modified from Das, 1994).

7.0 MAXIMUM LEVEE HEIGHT

Step 1. Calculate the load imposed by the generic levee section, as a function of X, using equations 3-1, 3-2, and 3-3 (Appendix 1).

Step 2. Using Figure 6, define the Bearing Capacity Factors for each of the 5 stratigraphic units (Appendix 2).

Step 3. Evaluate Terzaghi's General Equation for Ultimate Bearing Capacity (eq. 6-1), as a function of X, for each stratigraphic unit (Appendix 3).

Step 4. Set the load imposed by the generic levee section equal to Terzaghi's General Equation for Ultimate Bearing Capacity, simplify, and solve for X using the quadratic equation (Appendix 4).

The maximum levee height, as a function of each stratigraphic unit, is found in Table 2.

Unit	X
	(ft)
Alluvium	57.87
Sherack	57.87
Upper Brenna	0
Lower Brenna	2.66
Falconer	76.96

Table 2. Solution of Maximum Levee Height per Formation.

Step 5. Evaluate maximum levee height as a function of Factor of Safety.

Using the following methodology, a Factor of Safety is applied to the ultimate bearing capacity to determine the allowable bearing capacity:

$q_{all} = q_0 / F_s$ (Das, p.477) **(eq. 7-1)**

$X = X_0 / F_s$ **(eq. 7-2)**

The allowable bearing capacity is directly proportional to the ultimate bearing capacity. Factor of safety is indirectly proportional to the maximum levee height (increase F_s, decrease maximum height). Therefore, divide the maximum levee height values by the assumed F_s (eq.7-2), to correct height values (Table 3).

Unit	X	X	X
	(ft)	(F_s = 2)	(F_s = 3)
Alluvium	57.87	28.94	19.29
Sherack	57.87	28.94	19.29
Upper Brenna	0	0.00	0.00
Lower Brenna	2.66	1.33	0.89
Falconer	76.96	38.48	25.65

Table 3. Maximum Levee Height, per Unit, as a Function of F_s.

Step 6. Modification I of Terzaghi's Ultimate Bearing Capacity Equation.

I have calculated the maximum levee height over each of five units. Section 1 describes the stratigraphy at our construction site. The relative unit thickness' are taken as a percentage of the total depth surveyed to yield a percent weight as per unit (Table 4). These percentages are then multiplied by the total height supportable by each individual unit. The total maximum levee height over the proposed stratigraphy is the sum over each unit (eq. 7-3).

$$X = x_{alluvium} + x_{Sherack} + x_{Upper\ Brenna} + x_{Lower\ Brenna} + x_{Falconer} \quad \text{(eq. 7-3)}$$

where $x_{alluvium}$ = levee height supported by the alluvium unit
$x_{Sherack}$ = levee height supported by the Sherack Formation
$x_{Upper\ Brenna}$ = levee height supported by the Upper Brenna Formation
$x_{Lower\ Brenna}$ = levee height supported by the Lower Brenna Formation
$x_{Falconer}$ = levee height supported by the Falconer Formation

Unit	Thickness	Representative Thickness	X	Representative X
	(ft)	(%)	(F_s = 2)	(ft)
Alluvium	9.3	16.32	28.935	4.72
Sherack	8.04	14.1	28.935	4.08
Upper Brenna	25.38	44.53	0	0.00
Lower Brenna	8.34	14.63	1.33	0.19
Falconer	5.94	10.42	38.48	4.01
Total	57	100		13.01

Table 4. Maximum Levee Height as a Function of Site Stratigraphy, as calculated with Terzaghi Modification I.

The maximum levee height as a function of Red River Valley foundation sediments as calculated by Modification I of Terzaghi's Ultimate Bearing Capacity Equation = 13.01 feet, assuming a F_s of 2.0. Figure 7 illustrates the designed levee section. The Volume of this section = 468.62 ft^3 per linear foot (eq. 3-1).

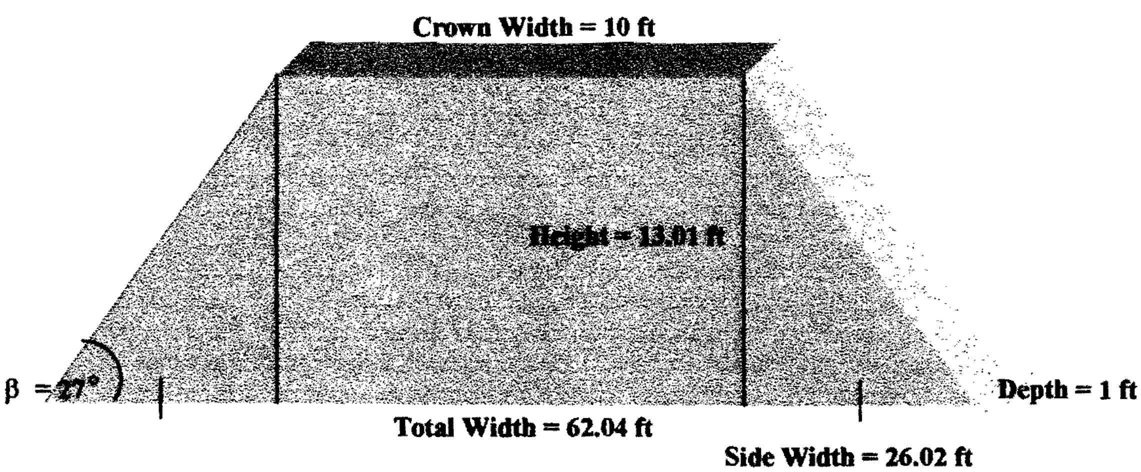


Figure 7. Designed levee section generated through Modification I of Terzaghi's Ultimate Bearing Capacity of Red River Valley Foundation Sediments.

(Not to Scale.)

Step 7. Modification II of Terzaghi's Ultimate Bearing Capacity Equation.

A second modification of Terzaghi's Equation developed (Phillips, 1998). Maximum height can be calculated as a function of bearing capacity failure surface rather than proportion of the

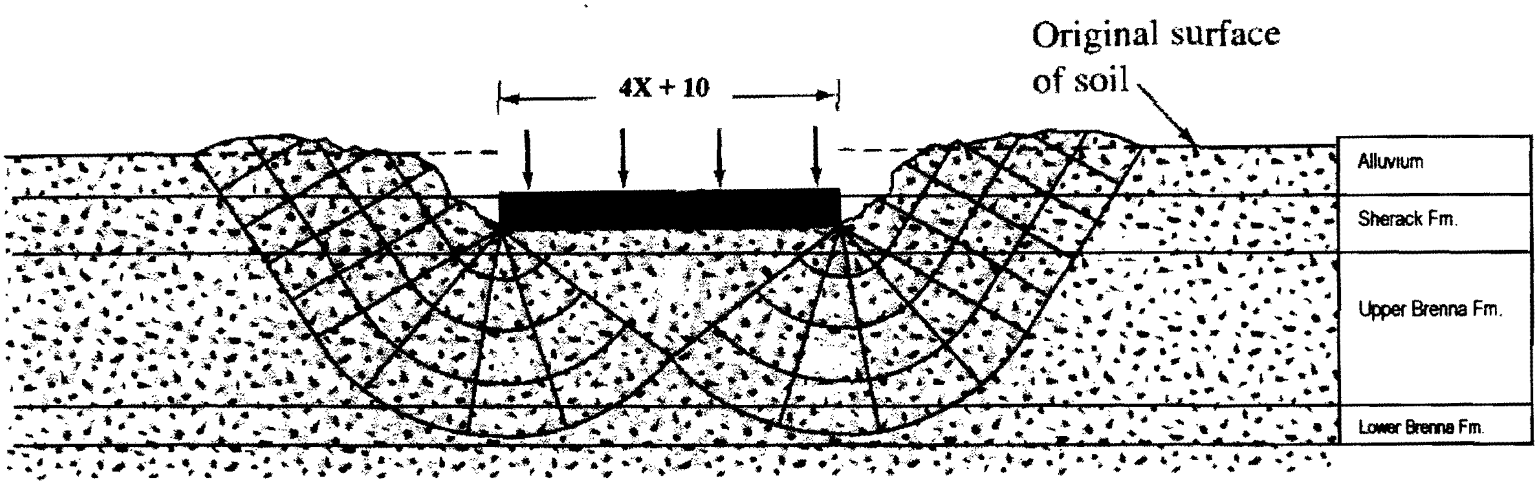


Figure 9. Stratigraphy and Bearing Capacity Failure Surface (modified after Das, 1994).

total stratigraphic composition. To proceed with this method of analysis it is necessary to make one additional assumption: the failure surface is contained within the weak Brenna Formation. Under this assumption, the diagram itself can be graphically scaled, and a representative length of failure surface can be measured to identify a new controlling proportionality factor (Table 5).

The maximum levee height as a function of Red River Valley foundation sediments as calculated by Modification II of Terzaghi's Ultimate Bearing Capacity Equation = 6.36 feet, assuming a F_s of 2.0. Figure 9 illustrates the designed levee section. The Volume of this section = 144.50 ft^3 per linear foot (eq. 3-1).

Unit	Failure Length	Control	X	Representative X
	(cm)	(%)	($F_s = 2$)	(ft)
Alluvium	1	10	28.935	2.8935
Sherack	1	10	28.935	2.8935
Upper Brenna	3.7	37	0	0
Lower Brenna	4.3	43	1.33	0.5719
Total	10	100		6.36

Table 5. Maximum Levee Height as a Function of Site Stratigraphy, Terzaghi Modification II.

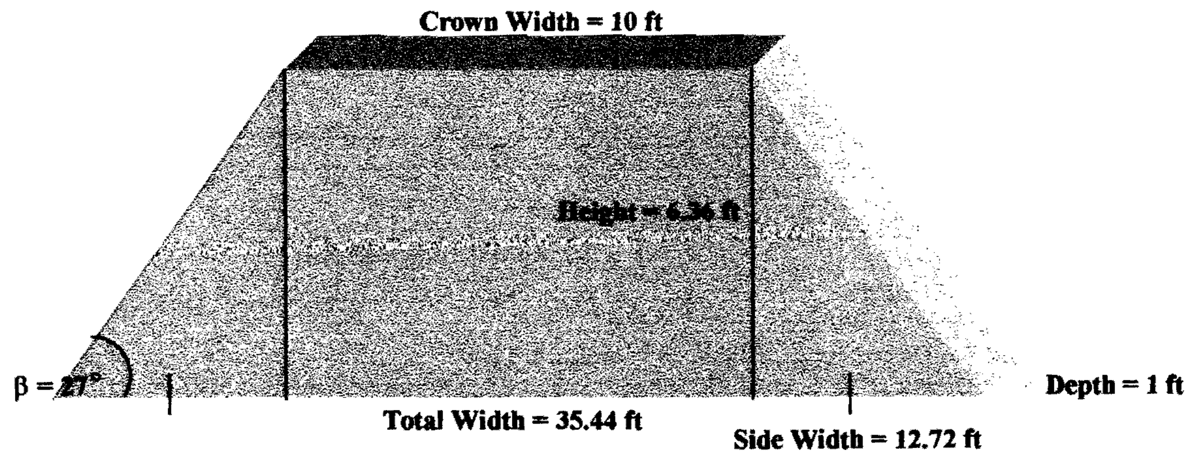


Figure 7. Designed levee section generated through Modification II of Terzaghi's Ultimate Bearing Capacity of Red River Valley Foundation Sediments. (Not to Scale.)

8.0 CONSTRUCTION COST ESTIMATE

The most reasonable way to generate a levee construction cost estimate is per linear foot. Construction involves stripping of topsoil and vegetation from the ground surface, clearing and grubbing of trees if required, placing levee fill material, and placing the topsoil and seed on the levee (City of Grand Forks & USACE, 1998.) Table 6 illustrates material costs as estimated in the "Feasibility Study for Local Flood Protection." For construction purposes we will utilize the larger designed levee section (Terzaghi Modification I). The projected raw material cost estimate per linear foot at the defined section is approximately $275.00.

	units	quantity	unit price	Estimated Price
Fill Material	ft^3	475	$0.56	$266.00
Topsoil	ft^3	23.75	$0.24	$5.70
Seed	ft^2	60	$0.01	$0.60
			Total Per Foot =	$272.30

Table 6. Raw Material Cost per Linear Levee Foot.

Additional cost per linear foot includes clearing the site, excavating and stockpiling fill, and spreading seed and topsoil (RS Means, 1997). Table 7 illustrates additional costs as estimated. The projected additional cost at the defined section is approximately $285.00.

	units	quantity	unit price	Estimated Price
Clear Site	ft^2	62.04	$0.074	$4.59
Excavate/Stockpile Fill	ft^3	475	$0.57	$270.75
Spread Topsoil	ft^3	23.75	$0.26	$6.18
Place Seed	ft^2	70	$.008	$0.56
			Total Per Foot =	$282.08

Table 7. Additional Cost per Linear Levee Foot.

The total preliminary cost per linear foot = raw material + additional = $560.00. (It is important to note this estimate does not include costs associated with levee construction as specifications regarding compaction or other special modifications (drainage, etc.) are unknown at this time.) The total estimate is then multiplied by a location factor (0.842) established for Grand Forks, North Dakota (RS Means, 1997) for a final construction estimate of $471.52 or approximately **$475.00 per lineal foot**.

9.0 CONCLUSIONS

Terzaghi's methodology for calculating ultimate bearing capacity is widely used for silts and clays; there much evidence to substantiate the validity of this approach (Tomlinson, 1975), yet there have been few studies regarding the ultimate bearing capacity of foundations on layered soils (Das, 1994). Both modifications of Terzaghi's Ultimate Bearing Capacity Equation attempt compensation for the layered strata.

The Red River Valley's glacio-lacustrine sediments provide a particularly weak construction foundation. In fact, the area stratigraphy is analogous to crust on pudding: not capable of providing support for a large levee system.

10.0 RECOMMENDATIONS

The maximum calculated levee height at the Kennedy Bridge locale is approximately 13.5 ft (Modification I) or 6.6 ft (Modification II). Preliminary USACE estimates indicate Levee height of 11.2 ft (Appendix 5) necessary for flood protection (assuming an event similar to Spring 1997) in this area. The estimated height is precariously close or exceeds the total maximum allowable height.

A factor of safety of 2 was utilized in this analysis. Upon literature review it has become apparent that a minimum factor of safety of 3-4 is considered appropriate for construction purposes (Das, 1995). Allowable levee heights with desired safety factors (3-4) are less than levee heights necessary for flood protection.

Strata contacts are zones of weakness, and failure on these surfaces could be induced by a lesser load. Construction may require compaction of the fill material, increasing the unit weight, and load per unit height. Further, this analysis does not account for differential stresses resulting from the load of flood water on the wet side, or the possibility of slope failure due to levee proximity to the river. It is very possible failure could occur at a much lesser height than that calculated by my methodologies.

In light of this fact, a careful survey of the official methodology used to calculate bearing capacity of the Red River Valley Foundation Sediments is necessary before proceeding on to construction stage.

References

City of Grand Forks & USACE, February 1998, "Flood Reduction Studies for East Grand Forks, Minnesota, and Grand Forks, North Dakota – Plan Comparison Letter Report."

City of Grand Forks & USACE, 1998, "Supplementary Documentation to the Plan Comparison Letter Report: Technical Appendices A-D."

City of Grand Forks & USACE, 1995, "Feasibility Study for Local Flood Protection."

City of Grand Forks, 1994, Topographic Map.

Das, Braja M., 1994, "Principals of Geotechnical Engineering," third edition, PWS Publishers, 424p.

Das, Braja M., 1995, "Principals of Foundation Engineering," third edition, PWS Publishers, 828p.

Meyerhof, George, 1982, "The Bearing Capacity and Settlement of Foundations," Tech-Press, 556p.

Phillips, Monte, 1998, Personal Communication, September 23rd.

RS Means, 1997, "Site Work and Landscape Cost Data," 16th Annual Edition, RS Means Company, Inc., 584p.

Sowers, G.B., and Sowers, G.F., 1961, "Introductory Soil Mechanics and Foundations," third edition, The Macmillian Company, 672p.

Terzahgi, Karl, and Peck, Ralph, 1967, "Soil Mechanics in Engineering Practice," second edition, John Wiley and Sons, Inc., New York, London, Sydney, 729p.

Tomlinson,M.J., 1975, "Foundation Design and Construction," third edition, John Wiley and Sons, New York – Toronto, 785p.

USACE, 1970, Engineering and Design Manual EM-1110-2-1902, "Stability of Earth and Rock-Fill Dams."

USACE, 1978, Engineering and Design Manual EM 110-2-1913, "Design and Construction of Levees."

Appendix 1

Load Imposed by the Generic Levee Section

Equation 3-1

$$\begin{aligned}\text{Volume} &= H * W * D \\ &= X * (2X + 10) * (1\text{ ft}) \\ &= 2X^2 + 10X\end{aligned}$$

H = X = Levee Height
W = Levee Width
D = Linear Depth

Equation 3-2

$$\begin{aligned}\text{Weight} &= V * \gamma_{fill} \\ &= (2X^2 + 10X) * 122\text{ lb/ft}^3 \\ &= 244X^2 + 1220X\end{aligned}$$

V = Levee Volume per Linear Ft
γ_{fill} = Unit Weight Fill

Equation 3-3

$$\begin{aligned}\text{Load} &= \text{Wt / Footprint Area} \\ &= (244X^2 + 1220X) / (4X + 10)\end{aligned}$$

Wt = Levee Weight per Linear Ft
Footprint Area = area per linear foot over which load is distributed

Appendix 2

Bearing Capacity Factors for Each Stratigraphic Unit

Unit	N_γ	N_c	N_q
Alluvium	0.8	8.5	2.25
Sherack	0.8	8.5	2.25
Upper Brenna	0.16	6	1.2
Lower Brenna	0.34	6.5	1.4
Falconer	0.48	7.45	1.75

Appendix 3

Calculation of Bearing Capacity for Each Stratigraphic Unit

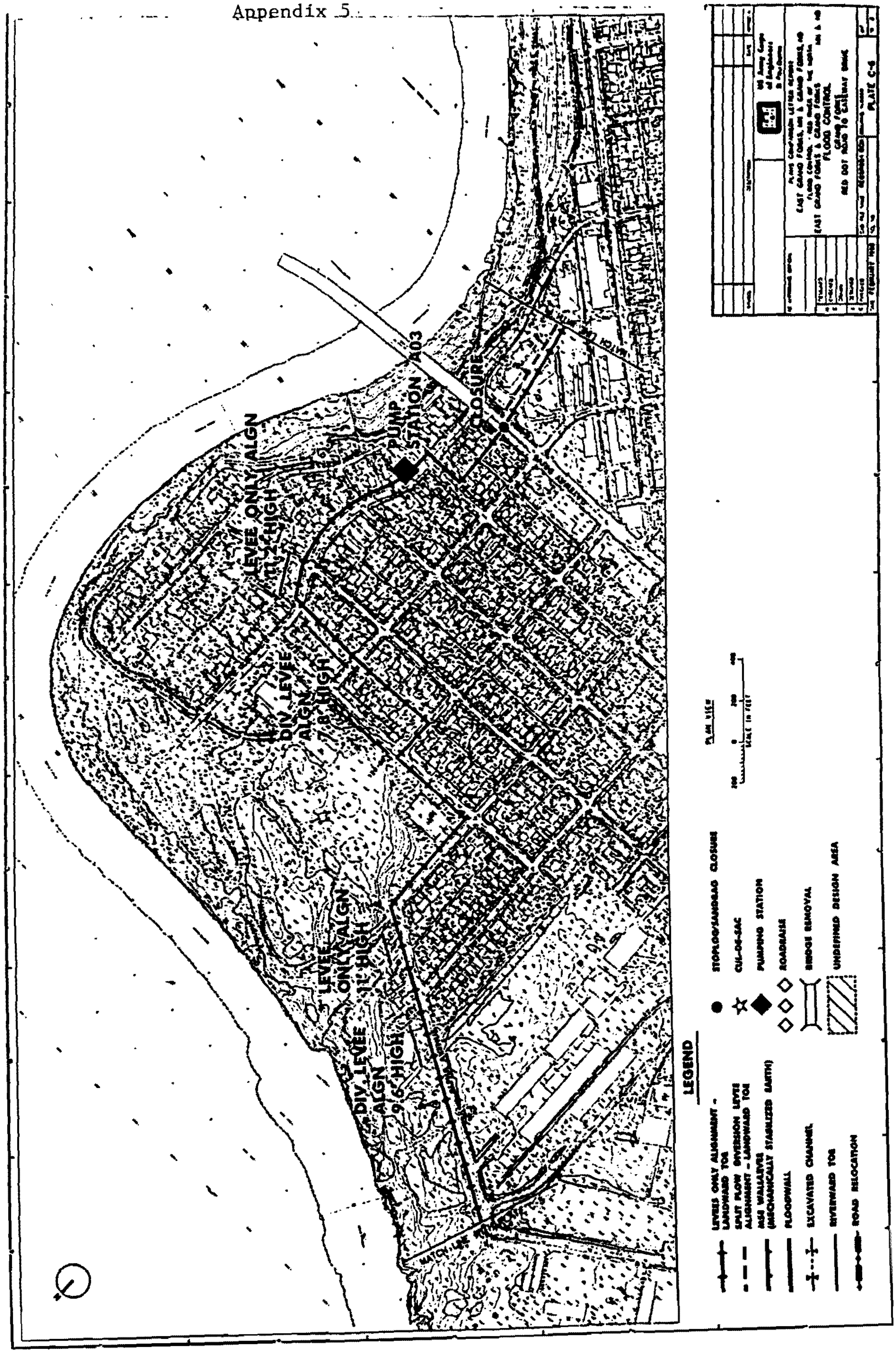
Unit	$q_0 = [(1/2)*\gamma*B*N_\gamma])] + [c*N_c] + [q*N_q]$
	(lb/ft^2)
Alluvium	195.2X +7925.5 + 0
Sherack	195.2X +7925.5 + 0
Upper Brenna	32X + 2180 + 0
Lower Brenna	74.8X + 2624.5 + 0
Falconer	120.96X + 4772.4 + 0

Appendix 4

Terzaghi's General Bearing Capacity Equation Set Equal to Load Imposed by Generic Levee Section

Unit	q_0 = levee load	X
Alluvium	$195.2X + 7925.5 = (244X^2 + 1220X) / (4X + 10)$	57.87
Sherack	$195.2X + 7925.5 = (244X^2 + 1220X) / (4X + 10)$	57.87
Upper Brenna	$32X + 2180 = (244X^2 + 1220X) / (4X + 10)$	0
Lower Brenna	$74.8X + 2624.5 = (244X^2 + 1220X) / (4X + 10)$	2.66
Falconer	$120.96X + 4772.4 = (244X^2 + 1220X) / (4X + 10)$	76.96

Appendix 5


LEVEE ONLY ALGN
11' HIGH
PUMP
STATION
A03
CLOSURE
DIV LEVEE
ALGN
8' HIGH
LEVEE
ONLY ALGN
11' HIGH
DIV LEVEE
ALGN
9.6' HIGH
LEGEND
LEVEES ONLY ALIGNMENT - LANDWARD TOE
FLOODWALL
EXCAVATED CHANNEL
RIVERWARD TOE
ROAD RELOCATION
STOPLOG/SANDBAG CLOSURE
CUL-DE-SAC
PUMPING STATION
ROADRAISE
BRIDGE REMOVAL
UNDEFINED DESIGN AREA
PLAN VIEW
SCALE IN FEET