CARL E. NORMAN, PH.D.
P.G. 1772; CPG 6831

CONSULTING GEOLOGIST

12625 MEMORIAL DRIVE #77
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SPECIALIZING IN ACTIVE GEOLOGIC FAULTS ON THE GULF COASTAL PLAIN

August 12, 2013

ARCADIS U. S., INC.
2929 Briarpark Drive
Suite 300
Houston, Texas 77042

Attention: Joe Ellison, Jr. E.I.T.

SUBJECT: PHASE III GEOLOGIC FAULT STUDY OF FOUR SEWER LINE CORRIDORS IN AN AREA SOUTHWEST OF THE INTERSECTION OF INTERSTATE HIGHWAY 10 AND THE 610 WEST LOOP IN WEST HOUSTON, TEXAS.

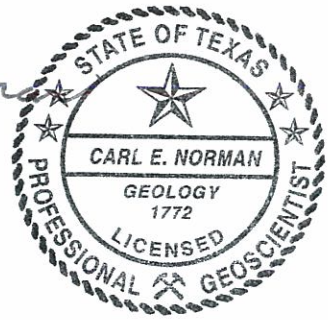
Transmitted herewith is my report on a geologic fault investigation of an area bordered on the north by Memorial Drive, on the west by East Friar Tuck Lane, on the east by North Post Oak Lane and on the south by Woodway Drive. The area includes four sewer line corridors that extend a total of approximately 3.5 miles. Only one surface fault, the Eureka Heights Fault, will cross the planned corridors. The crossings will be at three streets in the Stablewood residential subdivision.

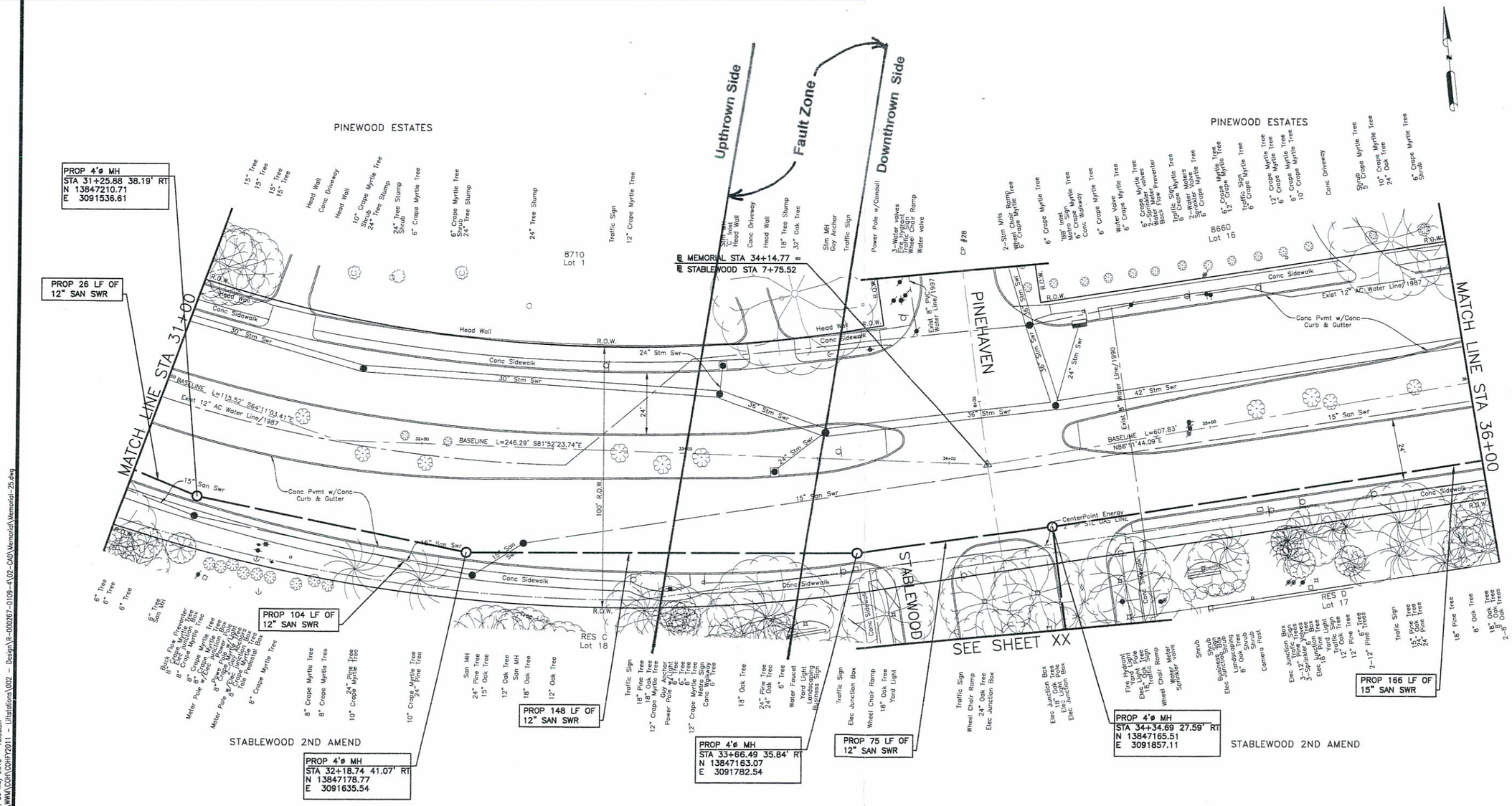
The report includes 4 maps that show the location, directional trend and width of the zone of disturbed ground along the fault. Three diagrams show the local components of ground motion parallel and perpendicular to the sewer lines at the street crossings. One diagram shows data relating to past movement rates of the fault at a nearby measurement station. These data are in turn used to predict the 3-dimensional pattern of ground movement the sewer lines will need to accommodate at the fault crossing points over the next 50 years. I appreciate the opportunity to conduct this investigation. Please let me know if I can provide you with additional information or assistance.

Sincerely yours,

Carl E. Norman

Carl E. Norman, Ph.D.
Consulting Geologist
P.G. 1772; CPG 6831





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TBM:

CP–28, SET MAG NAIL AT
STA 34+14.77
EL. 57.88

60% SUBMITTAL

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Texas Registered Engineering Firm F-533

DATE: MAY 2013
JOB NO. TX000941.0002

DESIGNED BY: EN
DRAWN BY: WW

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EDUARDO QUIROZ
TEXAS P.E. No. 85559

MAY 2013
DATE

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CITY OF HOUSTON
DEPARTMENT OF PUBLIC WORKS AND ENGINEERING

LIFT STATION
RENEWAL / REPLACEMENT
PROJECT

PLAN
MEMORIAL
STA 31+00 TO STA 36+00

C25

WBS#: R-000267-0109-4

DRAWING SCALE:
1"=20'

CITY OF HOUSTON PM
AKHTER HUSSAIN, P.E.

SHEET NO. OF

STATE OF TEXAS
CARL E. NORMAN
GEOLOGY
1772
LICENSED
PROFESSIONAL GEOSCIENTIST

FIGURE 2

LOCATION OF EUREKA HEIGHTS FAULT ZONE ACROSS MEMORIAL DRIVE

Fault Zone Location By
Carl E. Norman, Ph. D.
Consulting Geologist
P.G. 1772; CPG 6831
August 2013

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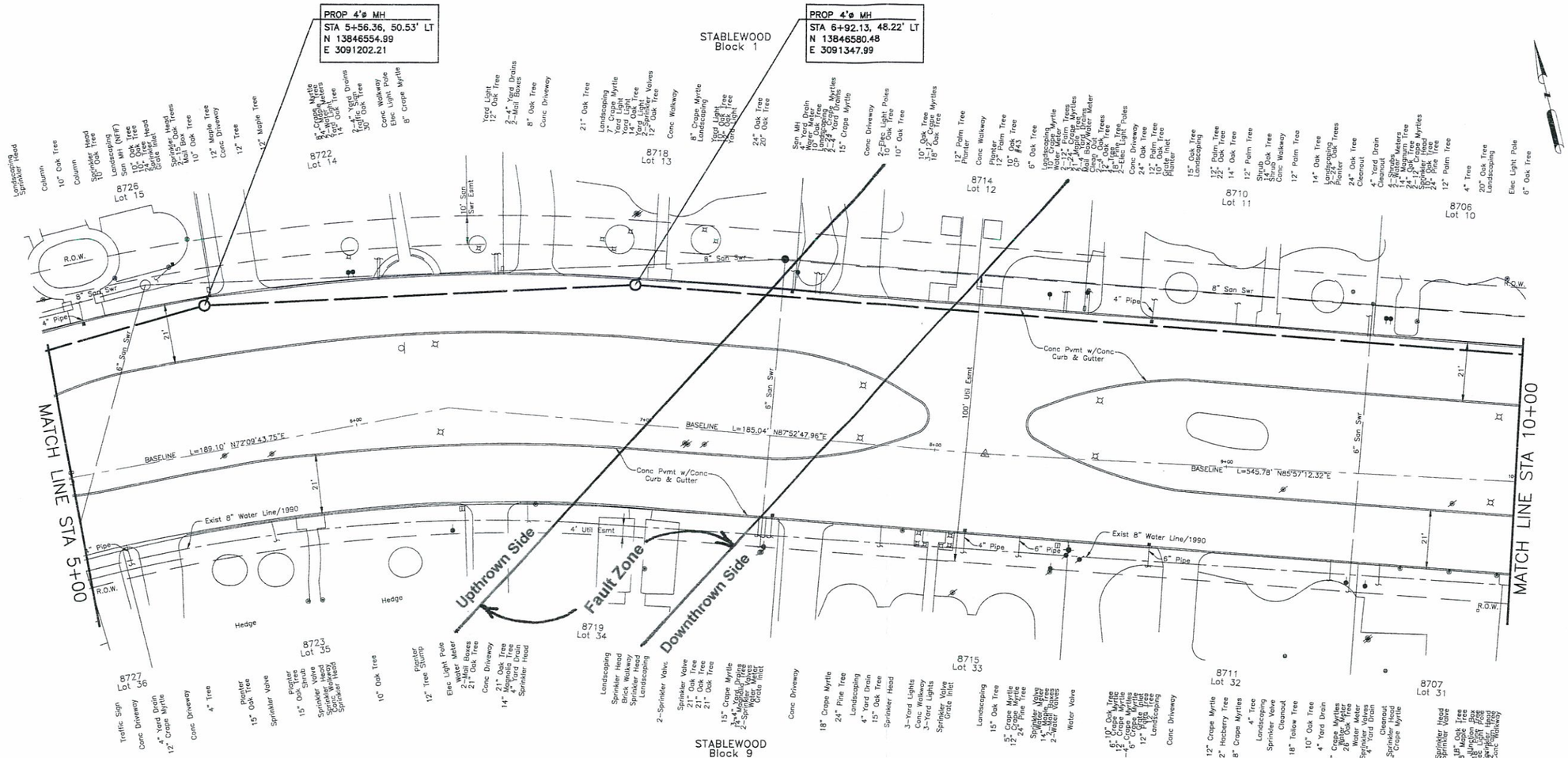

STABLE CREST

(SEE SHEET C59 FOR PROFILE)

STATE OF TEXAS
CARL E. NORMAN
GEOLOGY
1772
LICENSED
PROFESSIONAL GEOSCIENTIST

FIGURE 3

LOCATION OF EUREKA HEIGHTS FAULT ZONE ACROSS STABLE CREST BOULEVARD

Fault Zone Location By
Carl E. Norman, Ph.D.
Consulting Geologist
P.G. 1772; CPG 6831
August 2013

BENCH MARK:

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STA 6+02.35
EL. 37.44

TBM:
CP–43, SET MAG NAIL AT
STA 8+17.10
EL. 57.79

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MAY 2013
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CITY OF HOUSTON
DEPARTMENT OF PUBLIC WORKS AND ENGINEERING

LIFT STATION RENEWAL / REPLACEMENT PROJECT

PLAN
STABLE CREST
STA 5+00 TO STA 10+00

C58

WBS#: R-000267-0109-4

DRAWING SCALE:
H:1"=20' V:1"=2'

CITY OF HOUSTON PM
AKHTER HUSSAIN, P.E.

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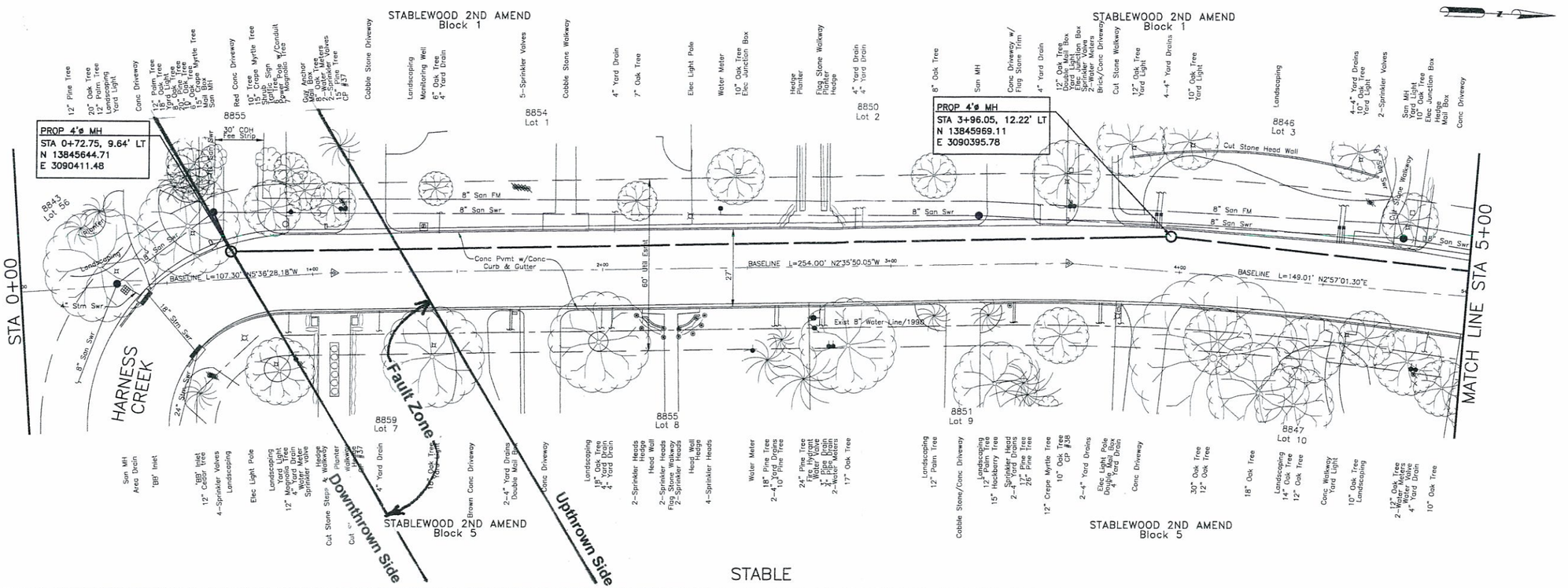

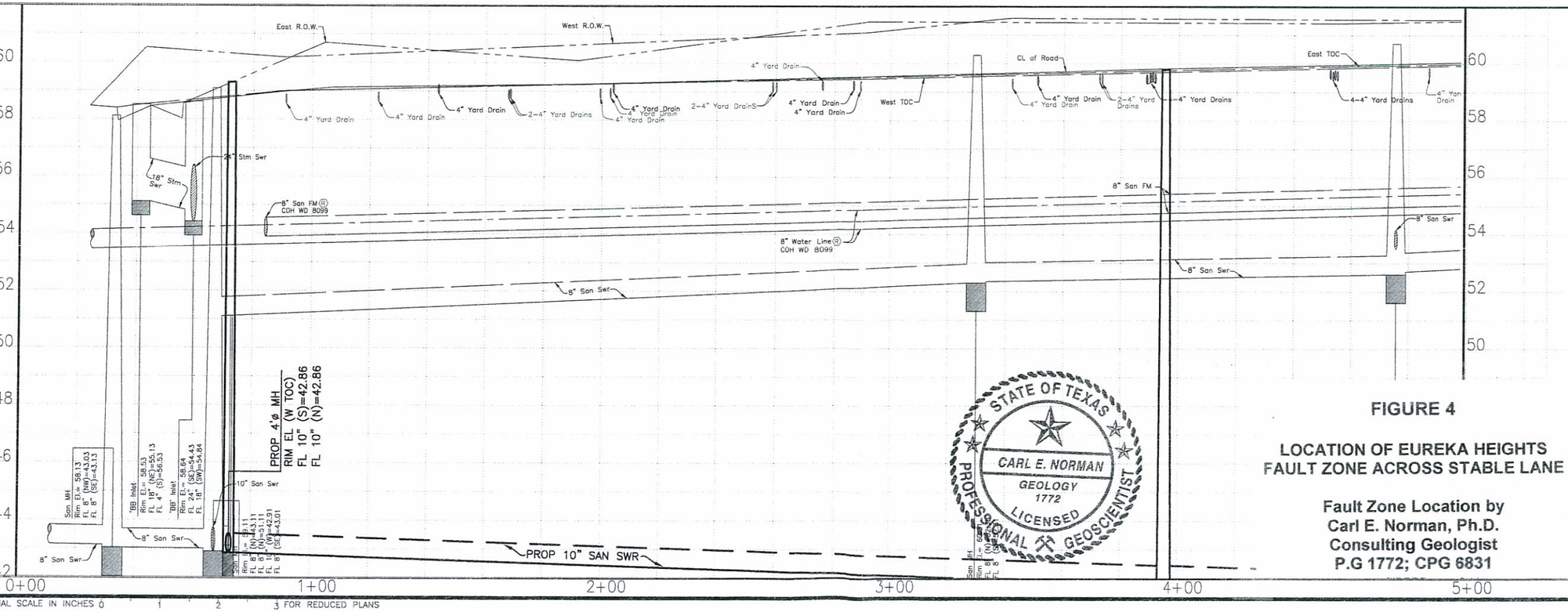

STATE OF TEXAS
CARL E. NORMAN
GEOLOGY
1772
LICENSED
PROFESSIONAL GEOSCIENTIST

FIGURE 4

LOCATION OF EUREKA HEIGHTS FAULT ZONE ACROSS STABLE LANE

Fault Zone Location by Carl E. Norman, Ph.D. Consulting Geologist P.G 1772; CPG 6831

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STA 1+07.30
EL. 59.15

CP-38, SET MAG NAIL AT
STA 3+61.30
EL. 59.72

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CITY OF HOUSTON
DEPARTMENT OF PUBLIC WORKS AND ENGINEERING

LIFT STATION RENEWAL / REPLACEMENT PROJECT

PLAN AND PROFILE-
STABLE STA 0+00 TO STA 5+00

C51

WBS#: R-000267-0109-4

DRAWING SCALE:
H:1"=20' V:1"=2'

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AKHTER HUSSAIN, P.E.

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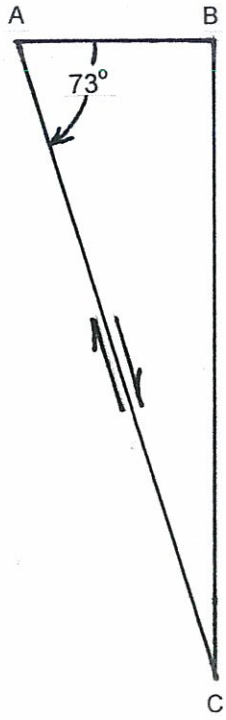
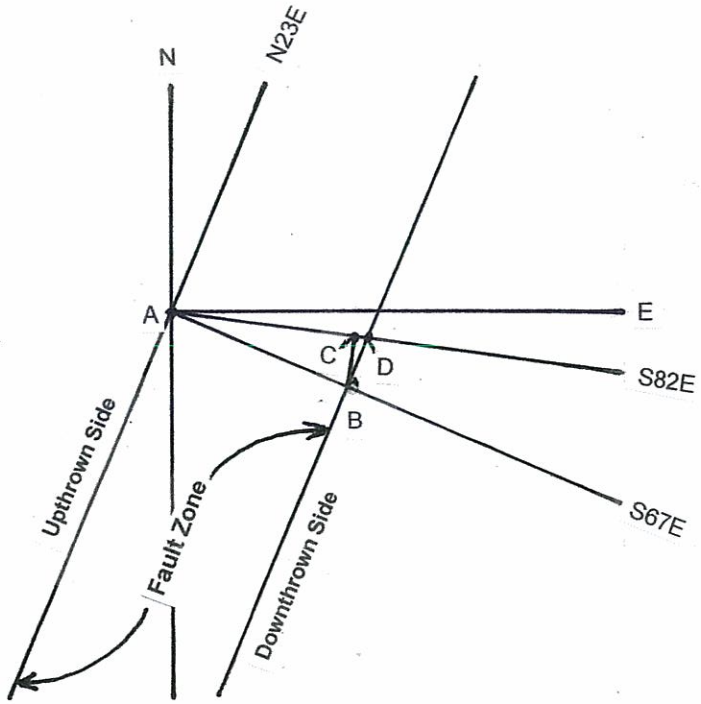


AB Horizontal Slip = 0.306 feet

BC Vertical Slip = 1.000 feet

AC Net Slip = 1.047 feet

Figure 5a. Vertical section view of fault slip components at Memorial Drive



AB Slip in True Dip Direction = 0.306 feet

AC Slip Parallel to Sewer Line = 0.295 feet

CB Slip perpendicular to Sewer Line = 0.079 feet

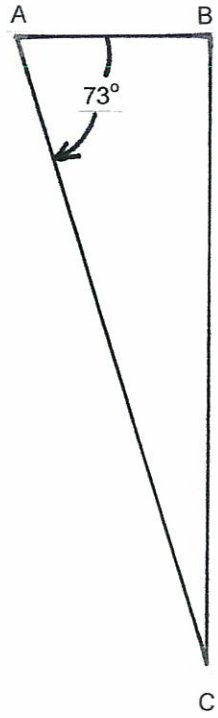
AD Apparent Width of Fault Zone Parallel to Sewer Line = 51.8 feet

N23E Fault Strike Direction

S67E Fault True Dip Direction

S82E Street Direction

Figure 5b. Map view of fault slip components at Memorial Drive

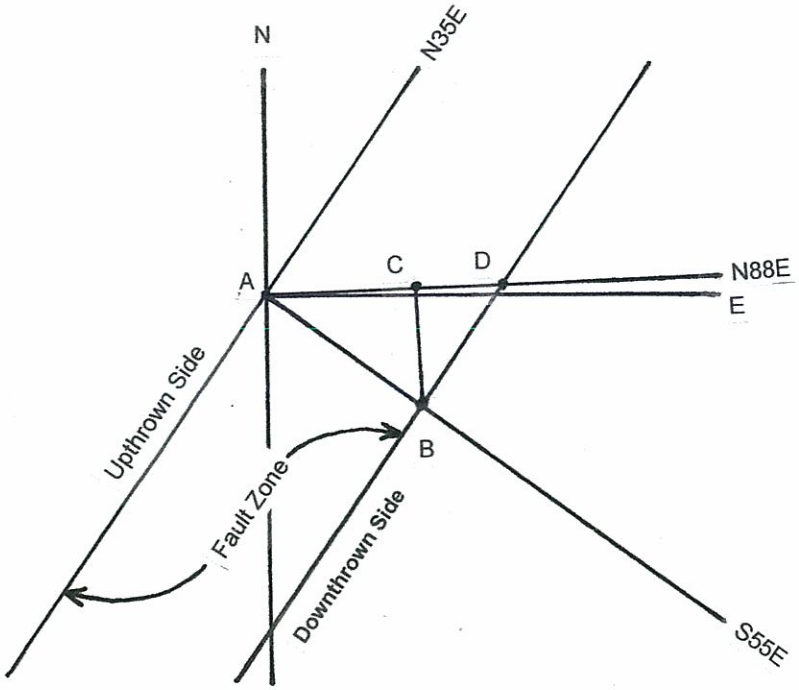


AB Horizontal Slip = 0.306 feet

BC Vertical Slip = 1.000 feet

AC Net Slip = 1.047 feet

Figure 6a. Vertical section view of fault slip components at Stable Crest



AB Slip in True Dip Direction = 0.306 feet

AC Slip Parallel to Sewer Line = 0.244 feet

CB Slip perpendicular to Sewer Line = 0.184 feet

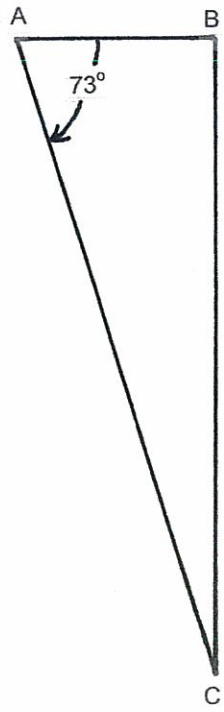
AD Apparent Width of Fault Zone Parallel to Sewer Line = 62.6 feet

N35E Fault Strike Direction

S55E Fault True Dip Direction

N88E Street Direction

Figure 6b. Map view of fault slip components at Stable Crest

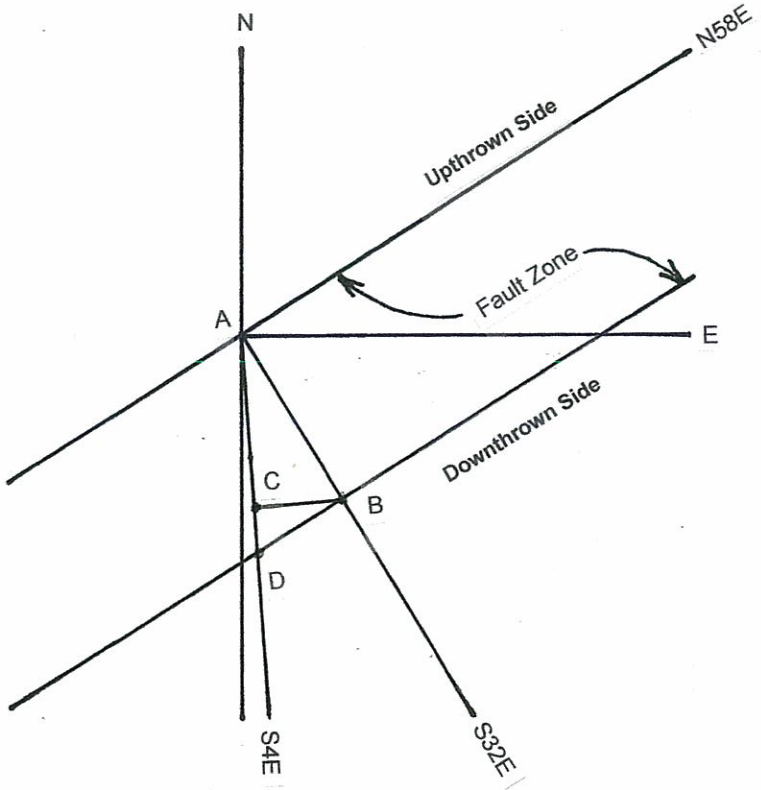


AB Horizontal Slip = 0.306 feet

BC Vertical Slip = 1.000 feet

AC Net Slip = 1.047 feet

Figure 7a. Vertical section view of fault slip components at Stable Lane



AB Slip in True Dip Direction = 0.306 feet

AC Slip Parallel to Sewer Line = 0.270 feet

CB Slip perpendicular to Sewer Line = 0.144 feet

AD Apparent Width of Fault Zone Parallel to Sewer Line = 56.6 feet

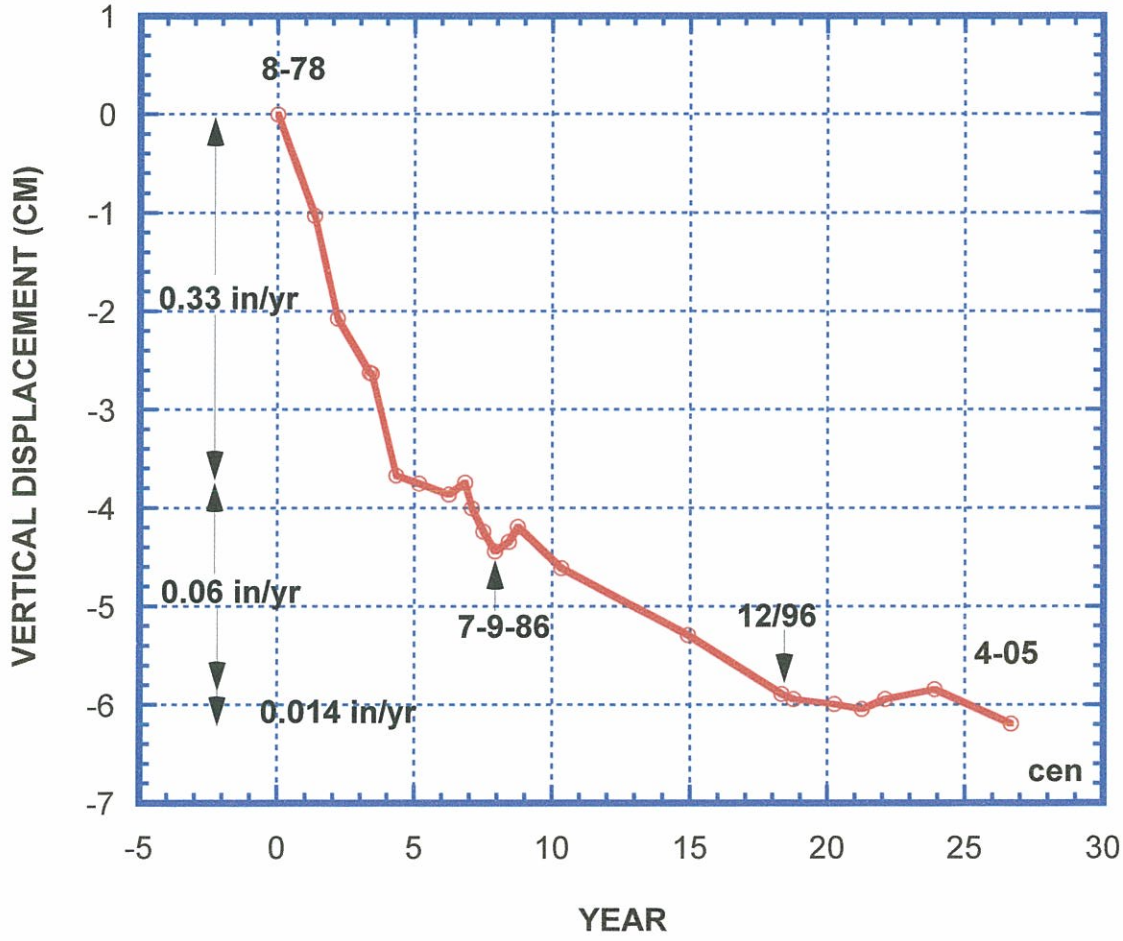
N58E Fault Strike Direction

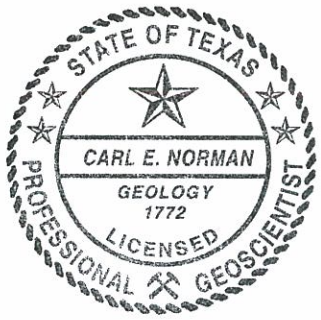
S32E Fault True Dip Direction

S4E Street Direction

Figure 7b. Map view of fault slip components at Stable Lane

FIGURE 8
EUREKA HEIGHTS FAULT
OLD KATY ROAD AT PORTWAY, HOUSTON, TEXAS
DISPLACEMENT VERSUS TIME, 1978-2005





PHASE III GEOLOGICAL FAULT STUDY OF FOUR SEWER LINE CORRIDORS IN THE AREA SOUTHWEST OF THE 610 WEST LOOP - INTERSTATE HIGHWAY 10 AREA IN WEST HOUSTON, TEXAS

For

THE CITY OF HOUSTON, TEXAS

Through

ARCADIS U. S., INC.
2929 BRIARPARK DRIVE
HOUSTON, TEXAS

By

Carl E. Norman, Ph.D.
Consulting Geologist
Houston, Texas

AUGUST 2013

CONTENTS

I. INTRODUCTION

The City of Houston plans to renew and replace sewer line lift stations and their connecting lines in west-central Houston. The project area is bounded on the north by Memorial Drive, on the east by Post Oak Lane, on the south by Woodway Drive, and on the west by E. Friar Tuck Lane. The broader goal of the study has been to identify any surface fault that might disturb ground across any of the lift stations and/or the sewer lines connecting them. Because it may be desirable to incorporate special provisions into the design of the stations and utility lines in a fault hazard zone, a goal was established to provide information on the precise location and orientation of a fault, the width of its hazard zone, and the geometry of relative motion of the fault blocks. I define the hazard zone as the zone of disturbed ground along a fault in which 90 percent or more of the differential movement of the upthrown and downthrown fault blocks takes place.

The methods of investigation included a survey of published and proprietary geological reports of surface faults in the study area; examination of petroleum industry maps of the deep subsurface geology, a study of aerial photographs and LiDAR images, and a field investigation to identify areas of natural disturbance of streets, sidewalks, buildings, fences and other man-made structures that could reasonably be attributed to an active fault. The study concludes that only one fault, the Eureka Heights Fault, disturbs ground within the project area. Figure 1 shows the locations where the fault intersects 3 streets in the study area.

The specific objectives of the present study are to:

1) establish the location of the Eureka Heights Fault at ground level where it crosses streets within the study area,
2) establish the 3-dimensional orientation of the fault at each sewer line crossing,
3) provide a measure of the width of the fault hazard zone,
4) establish the 3-dimensional pattern of differential ground movement that the sewer line must accommodate in the hazard zone, and
5) provide an estimate of the amount of differential ground movement the road and utility lines will need to accommodate over the next 50 years.

The objectives were achieved from observations and measurements at ground level. No new subsurface data were obtained in the course of the study. The measurements established the

location and local trend of the Eureka Heights Fault at each point where it crosses the centerline of streets within the study area. Repeated measurements of elevation changes in nearby bench marks that had been placed across the fault were used to establish a mean width for the fault zone as well as the fault's displacement history.

II. GENERAL CHARACTERISTICS OF THE EUREKA HEIGHTS FAULT

The Eureka Heights Fault extends northeastward about 7.2 miles from a point near Woodway Drive at Broad Oaks Drive East to a point near Interstate Highway 45 at Airline Drive. Everywhere along its length, ground southeast of it moves downward and southeastward relative to ground northwest of it. There appears to be no component of differential movement of ground in a horizontal direction parallel to the trend of the fault. In geologic terms, it is a strictly normal-slip fault. The fault trace at ground level is not a straight line. Its overall trend is N 50° E, but locally it deviates a few to several tens of feet left and right of a straight line. Figures 1, 2 and 3 are alignment maps that show the location and orientation of the fault relative to points along the planned sewer line alignments.

Subsurface data show that the fault dips (slopes downward) to the southeast. There are no known measures of the dip angle of the Eureka Heights Fault at shallow depths in the Post Oak Lane-Memorial Drive area. The nearest location where subsurface data became available to measure it is a few hundred feet southwest of the intersection of Bevis Street with the 610 North Loop. Here 3 of 4 geophysically logged boreholes, spaced 13 feet apart, penetrated the fault at depths of 48, 92 and 135 feet below grade. The true dip of the fault, measured in the direction perpendicular to the trend of the fault, is 73 degrees. Because that angle is typical for faults throughout the Houston area, it will be assumed to represent the dip of the Eureka Heights Fault where the planned sewer lines will intersect it in the study area.

Repeated measurements of elevation profiles on five lines that cross the Eureka Heights Fault show that the central parts of the fault tend to be the most active. Toward the ends of the fault, rates of differential ground movement become vanishingly small. The Post Oak Lane-Memorial Drive area is within a mile of the southwest end of the fault.

III. SURFACE EXPRESSION OF THE EUREKA HEIGHTS FAULT IN THE MEMORIAL-POST OAK LANE AREA

Prior to the 1990 development of residential areas southwest of the intersection of Memorial Drive with Post Oak Lane, the area through which the subject sewer lines and the Eureka Heights Fault pass, there was clear topographic expression of the fault southward across Memorial Drive to a point within about 500 feet of the north bank of Buffalo Bayou. Northeast of Memorial Drive the fault could be traced confidently for another 3 miles. These relationships are represented on a 1979 map of surface faults in north-central and western Houston (Verbeek and Clanton, U. S Geological Survey, Map MF-1136). Since construction of streets and residences in the Memorial Drive-Post Oak Lane area, rates of movement of the fault have been too low to produce an easily recognizable topographic scarp across the zone of ground disturbed by the fault. Nevertheless, recent bending of concrete-paved streets across the fault zone has generated a denser concentration of extension fractures than exists elsewhere. These fractured areas correspond with the location of the topographic scarps that formerly existed along the fault.

IV. THE FAULT ZONE

Determination of the width of a zone of disturbed ground along faults is best made by repeated measurement of changes in the elevation of closely-spaced bench marks across the zone. No such data base exists for the Eureka Heights Fault within the Memorial-Post Oak Lane area. However, an estimate of its width can be made from such measurements where the fault crosses W. 34th Street near Shepherd Drive (48 feet), Bevis Street at 610 North Loop (45 feet), Couch Street at 26th Street (33 feet), Washington Avenue at Walne Street (40 feet) and Post Oak Lane at Chatsworth Drive (63 feet). The average width is 46 feet. All 5 measures allowed for uncertainties in the interpretation of the elevation profiles and for some variation from an assumed linear trend of the fault across the streets.

For the present study, I have chosen to display a 50-foot wide fault zone. To increase certainty that the 50-foot distance includes the entire zone of ground disturbance, a wider zone may be adopted. If this is to be done, all of the additional width should be added to the upthrown side of the fault zone where the rate of ground movement is highest.

V. THE LOCATION AND THREE DIMEMSIONAL MOVEMENT PATTERN OF GROUND ACROSS THE FAULT AT EACH OF THE THREE STREET CROSSINGS.

Figures 2, 3 and 4 are large scale maps showing a 50-foot wide Eureka Heights fault zone crossing Memorial Drive, Stable Crest Boulevard and Stable Lane. Each map shows baseline locations along the center of the street from which the boundaries of the fault zone can be measured. The strike (trend) of the fault at each of the 3 fault crossings was determined from field observation and measurement.

Va. Memorial Drive Crossing

Figure 2 shows the fault zone crossing Memorial Drive approximately 100 feet west of Pine Haven Drive and Stablewood Boulevard. The upthrown side of the zone crosses the street at baseline No. 33+00 and the downthrown side at No. 33+52. From here forward it is assumed that the sewer line will parallel street baselines.

Figure 5a is a vertical section perpendicular to the strike of the fault. It shows the vertical and horizontal components of the net slip of the fault, which is 73° downward in direction S67E. At this dip angle, the downthrown fault block moves 0.306 feet horizontally in direction S67E for each foot that it drops vertically. The 0.306 feet of horizontal separation of the fault blocks constitutes a horizontal extensional strain in direction S67E.

Figure 5b shows the N32E strike of the fault and the S82E direction of the street baseline, indicating a crossing angle of 75°. It also shows the horizontal slip component (AB = 0.306 feet) resolved into components acting parallel (AC) and perpendicular (BC) to the direction of the street baseline. For each foot of vertical drop of the downthrown block, the extensional component of slip parallel to the street (AC) is 0.295 feet. Perpendicular to the street (CB) it is 0.079 feet. The diagram also shows that the apparent width of the fault, measured parallel to the street baseline, is 51.8 feet.

Vb. Stable Crest Boulevard Crossing

Figure 3 shows the fault zone crossing Stable Crest Boulevard. The upthrown side of the zone crosses at baseline No. 7+00 and the downthrown side at baseline No. 7+63.

Figure 6a shows the vertical and horizontal components of the net slip of the fault (AC) in its true dip direction of S55E. For a vertical drop of 1 foot (BC), the downthrown fault block moves horizontally, developing a horizontal extensional strain of 0.306 feet in direction S55E (AB).

Figure 6b is a horizontal section that shows the N35E strike direction of the fault and the S55E true dip direction. It also shows the street direction, N88E. The crossing angle between the street direction and the fault strike direction is 53 degrees. As a consequence, the distance required for the sewer line to cross the entire 50-foot wide fault zone (AD) is 62.6 feet. The horizontal slip component of 0.306 feet (AB) resolves to 0.244 feet acting parallel to the street baseline (AC) and 0.184 feet acting perpendicular to it (CB).

Vc. Stable Lane Crossing

Figure 4 shows the Eureka Heights Fault crossing Stable Lane near its intersection with Harness Creek Lane. The downthrown side of the fault crosses at baseline No. 0+78 and the upthrown side at baseline No. 1+35.

Figure 7a shows the horizontal and vertical components of net slip for the fault in direction S32E, its local true dip direction. As the downthrown fault block moves vertically downward 1 foot, it also moves horizontally 0.306 feet in direction S32E.

Figure 7b shows the N58E strike direction of the fault, its true dip direction of S32E and the local trend of the street, S4E. The crossing angle between the fault strike and the trend of the street is 62 degrees. Thus the apparent width of the fault zone, measured parallel to the local street baseline, is 56.6 feet. The horizontal slip component of 0.306 feet (AB) resolves into 0.270 feet acting parallel to the local street baseline and 0.144 feet perpendicular to it (CB).

Along each of the 3 street crossings discussed above, the vertical angle at which the fault zone dips in a direction parallel to the street is less than the 73 degree true dip of the fault. Although the angular relationships at the 3 crossings are different, they are such that this "apparent dip" of the fault is 70 $\pm$ 1 degrees at each crossing. The result is that at a depth of 10 feet below ground level, the fault zone will have migrated 3.64 feet horizontally in the apparent dip direction parallel to the street. At 20 feet it will have migrated 7.28 feet, and so forth.

VI. RATE OF DIFFERENTIAL MOVEMENT OF THE FAULT BLOCKS

The best means for determining current rates of relative movement of ground across a fault is to repeat measurements of the difference in elevation of bench marks placed entirely across the fault zone. Such data have not been recorded for the Eureka Heights Fault in the Stablewood subdivision, but do exist for the fault 6000 feet to the northeast where it crosses Old Katy Road at Portway Drive. They were obtained from bench marks installed by the U. S. Geological Survey and recorded by them and the present author for the period of August 1978 to April 2005. In that latter year the bench marks were destroyed during reconstruction of the roadway. From here forward I will assume that those data apply directly to the Stablewood area as well.

Figure 8 is a graph of the data. It is obvious that the fault remained continuously active over the 26.66-year period. On the left side of the graph are indicated average rates of vertical descent of the downthrown fault block relative to the upthrown block for three time periods. From August 1978 through December 1982 the rate averaged 0.33 inches per year. From then until May 1997 it descended at a rate of 0.06 inches per year, and from then until April 2005 the rate declined to 0.014 inches per year. The average rate of vertical descent of the downthrown block for the entire 26.66-year period was 0.09 inches per year.

Using the highest recorded vertical movement rate of 0.33 inches per year, we can predict somewhat conservatively that the streets and the sewer lines throughout the Stablewood subdivision will be displaced vertically 16.5 inches (1.375 feet) over the next 50 years. The horizontal component of motion will be 5.04 inches (0.421 feet) of extension in the direction perpendicular to the strike of the fault.

Using Figure 5b, the highest rates of movement parallel and perpendicular to the sewer line at Memorial Drive can be predicted for a 50-year period. The total horizontal slip there will be 1.375 X 0.306 = 0.421 feet. The component parallel to the sewer line will be 1.375 X 0.295 = 0.399 feet and the component perpendicular to the line will be 1.375 X 0.079 = 0.109 feet.

Using Figure 6b for the Stable Crest crossing, the total horizontal slip will be 0.421 feet, the horizontal component parallel to the sewer line will be 0.336 feet and the component perpendicular to the line will be 0.253 feet.

From Figure 7b the total horizontal slip at Stable Lane is 0.421 feet, the component parallel to the sewer line will be 0.371 feet and the component perpendicular to it will be 0.198 feet.

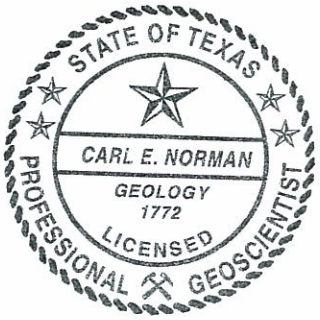
Similar calculations can be made if the reader wishes to determine components for the average rate of movement of the fault over the entire 26.66 year time span, or for each of the other two shorter time intervals shown on Figure 8.

It is important to note that our knowledge of the recent activity of this fault spans only about 35 years. The fault extends to depths of tens of thousands of feet, and it has been intermittently active for tens of millions of years. This report does not take into account any speculation, postulation or theorization as to the origin of the fault or the cause of its current activity. Until we have a better understanding of the mechanism and dynamics of fault movement in the Gulf Coastal Area, the only rational basis for predicting future rates of movement on the human time scale is to rely on the historical record.

VII. CONCLUSIONS

A surface study of the active Eureka Heights Fault in the Memorial Drive-Post Oak Lane area of west Houston shows that at ground level it crosses 3 streets in the Stablewood subdivision where a new sewer line is to be constructed. Assuming the upthrown fault block to be stable, the motion vector of the downthrown block plunges 73 degrees in a southeasterly direction. Both the trend of the fault and the direction of the streets differ at each of the 3 crossing points. The rate of relative movement of the upthrown and downthrown fault blocks has not been measured in the subdivision, but data for the vertical component of movement for a nearly 27-year period are available from a measurement station approximately 6000 feet northeast of it. They show a declining rate of movement that, over a period of 26.66 years, averages 0.091 inches per year. An early 4-year period shows the highest rate of 0.33 inches per year.

In order to obtain a conservative estimate of the amount of fault movement to expect at each of the 3 street crossings over the next 50 years, the calculations presented here are based on the highest observed rate of 0.33 inches per year. The result is a prediction of 16.5 inches (1.375 feet) of vertical displacement of the downthrown block over the next 50 years. Accompanying the vertical displacement is a horizontal southeastward extensional component of 5.04 inches (0.421 feet). Finally, the report determines the horizontal components of movement parallel and perpendicular to the sewer line at each of the 3 street crossings.



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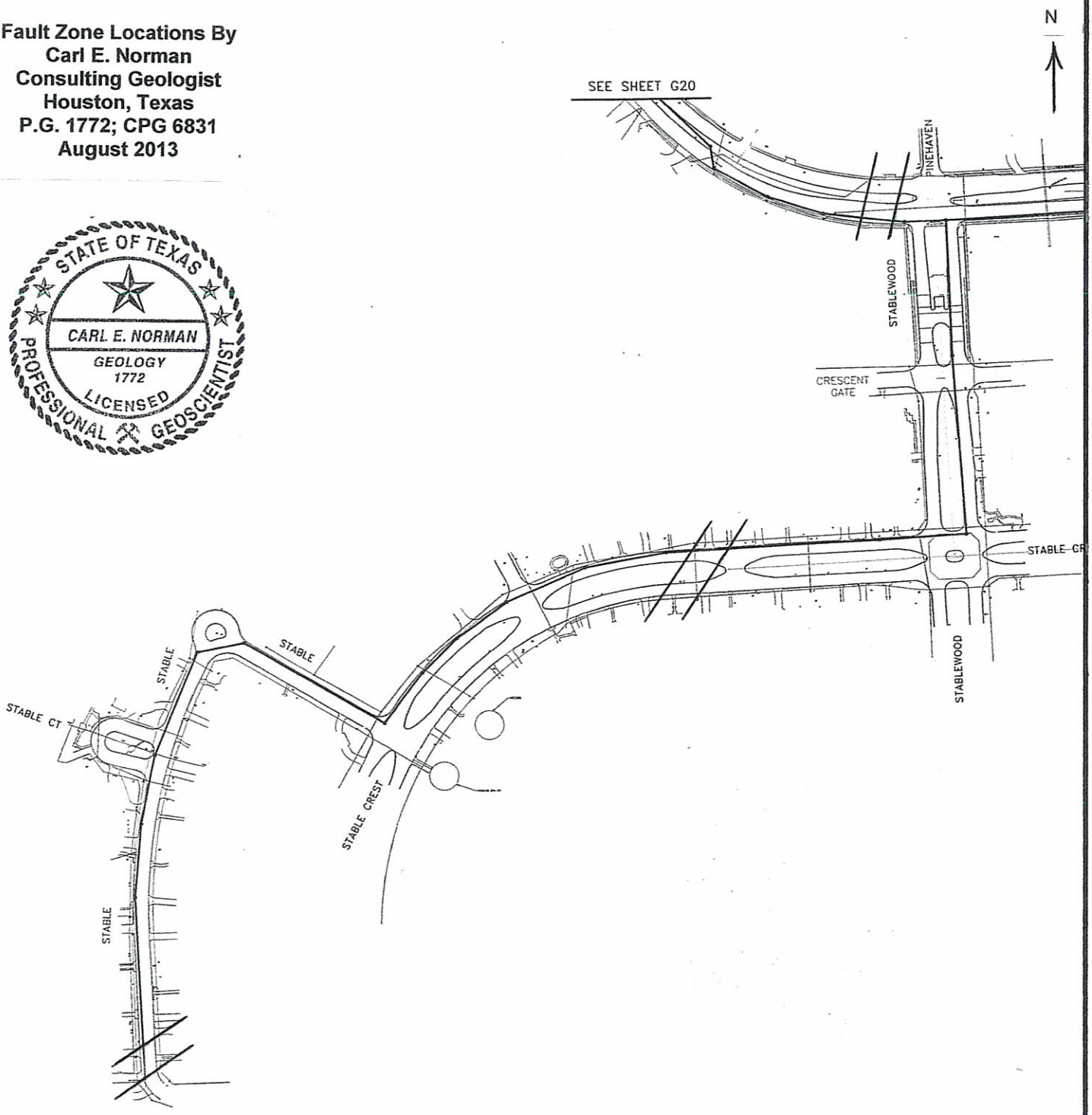

FIGURE 1

STREET CROSSINGS OF EUREKA HEIGHTS FAULT
MEMORIAL DRIVE-POST OAK LANE AREA
HOUSTON, TEXAS

0 260
Feet

½ ⅓ FOR REDUCED PLANS