Geotechnical Summary Report
Third Runway Embankment and MSE Retaining Walls
Seattle-Tacoma International Airport

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Prepared for
The Port of Seattle
for Presentation to
The U.S. Army Corps of Engineers

November 2, 2001
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Prepared by
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GEOTECHNICAL SUMMARY REPORT
THIRD RUNWAY EMBANKMENT AND MSE RETAINING WALLS
SEATTLE-TACOMA INTERNATIONAL AIRPORT

EXECUTIVE SUMMARY

This report describes the engineering process used to address design issues related to soil conditions, groundwater, and potential earthquakes for the proposed Third Runway at Seattle-Tacoma International Airport (STIA). Overall, the runway project will include placement of 17,000,000 cubic yards of compacted fill, 3,000,000 cubic yards of excavation, and construction of three "mechanically stabilized earth" (MSE) retaining walls that range from 50 to 135 feet in maximum height.

The executive summary of this report describes its purpose, general contents of the report, and results of the engineering analysis. A key part of the work described herein has been the involvement of an independent technical review board composed of distinguished experts to provide input into the geotechnical design process.

The main part of this report summarizes the geotechnical data collection and engineering analyses accomplished over a multi-year period by the Port of Seattle. The Seattle District, US Army Corps of Engineers (Corps) requested this executive summary as part of its review of the Third Runway Project.

Scope and Purpose of This Report

The scope of this report is to address the following:

- Introduce the reader to the design team and explain what each firm's role has been, including the involvement of outside reviewers;
- Describe the main features of the embankment and MSE retaining walls that are addressed in this report;
- Summarize information that has been collected on soil and groundwater conditions at the Third Runway site;
- Generally describe how the Port has studied the risk posed by earthquakes, and how seismic hazards are being addressed in the design process;
- Discuss the methods of engineering analyses used for design of the embankment slopes and retaining walls; and
- Describe how construction will include specific measures to mitigate problematic soil conditions, assure stability and meet seismic performance criteria.

The purpose of this report is to provide the Corps with a summary of the geotechnical work that has been accomplished for the Third Runway project, including references to other reports prepared by the Port's design team that provide more comprehensive discussion and details.

"Road Map" for Readers

A detailed table of contents, with lists of figures and tables, follows this executive summary. Thereafter:

- Section 1 is a general introduction to the Third Runway project and the engineering design team.
- Section 2 describes the geotechnical design process.
- Section 3 explains how soil and groundwater information was obtained and provides a geologic description of the project site.
- Section 4 discusses the methods of geotechnical engineering analyses used.
- Section 5 describes how the MSE wall design has incorporated geotechnical input and the results of independent checks and review.
- Section 6 discusses how construction will include "subgrade improvements" to mitigate problem soil conditions, and assure stability.

A bibliography of other reports that present geotechnical information for the Third Runway project follows the main text, along with a list of other technical references. Tables, figures, and the oversize plates cited in the text are included at the end of the report.

Engineering Quality Assurance

The Port of Seattle has assembled a team of notable engineering firms (HNTB, Hart Crowser, and RECo) to the design the Third Runway embankment and retaining walls. Qualifications of these firms to fill their specific roles, along with other experts who are providing support to the design team are discussed as part of the introduction to the design process, later in this report.

MSE retaining walls for the Third Runway are being designed in accordance with, and exceeding criteria established by the American Association of State Highway and Transportation Officials (AASHTO). Design of the project features is being accomplished with methods that are well-established and widely accepted by the engineering community. In addition, the Port has utilized advanced engineering analysis to check the design and evaluate performance of the Third Runway embankment and retaining walls. The Port's design meets or exceeds comparable "factor of safety" criteria used by the Corps for design of earth embankments (levees) and retaining walls.

To support the design team, the Port has used outside technical reviewers to provide independent assessment of various parts of the design process. The Embankment Technical Review Board (ETRB) members include Dr. James K. Mitchell, P.E., an expert in soil behavior, ground improvement, and earth reinforcement; Dr. I.M. Idriss, P.E., a recognized authority on earthquake engineering; and Dr. Barry Christopher, P.E., an internationally recognized expert in MSE wall design, construction, and performance.

The ETRB has worked closely with the Port's design team to develop an understanding of the Third Runway project and subsurface conditions at the site. The Board has provided detailed recommendations for improving design analyses and implementation of additional test and sophisticated analyses to improve the design. The Port's design team has addressed the Board's recommendations, and thereby enhanced the design. In addition to the ETRB, the Port has utilized other experts to provide independent technical input to the Third Runway design team, in several other specific instances since 1998.

This report describes specific input from the ETRB and others at different parts of the design process, which provides assurance that the work accomplished meets the highest technical standards.

Seismic Performance Goals for the Embankment and Walls

The Port has adopted seismic performance goals for the Third Runway embankment and MSE walls. The purpose of these goals is to clearly state the result of the geotechnical design process in terms that are easier to understand compared to the numeric factors of safety specified by the AASHTO code.

The Port of Seattle's design team gave considerable attention to selecting the level of earthquake shaking that would be used as the basis for design. This process considered statistical extrapolation of seismic data for our region, and explicitly considered the effect of variations in size, location and attenuation of future earthquakes. The methods used were subjected to scrutiny by the design team and the ETRB experts, and analyses by well-established methods were checked by independent methods to verify appropriateness of the design.

The Third Runway project is being designed as a "structure of ordinary importance" similar to large public buildings and other transportation infrastructure such as bridges and highways. In technical terms, the project is being designed to perform well for seismic ground motions that have a 10 percent probability of being exceeded in 50 years - or in other words, the level of shaking that has an average return period of 475 years.

Specific performance goals for the Third Runway project are to meet the following conditions for this design level of shaking:

- The MSE walls and embankment fill will remain stable. Some deformation is acceptable (up to a few feet) provided stress in the retaining wall materials are typically below the value allowed by the AASHTO code;
- There will be no wetland or creek impacts due to seismic shaking of the embankment or MSE walls; and
- There will be no operational impacts to the new runway related to movement of the embankment slopes and walls during an earthquake.

The engineering analyses described in this report have been accomplished iteratively with design modifications to assure the completed embankment slopes and MSE retaining walls will meet the performance objectives. As needed, the design has been modified by increasing the extent of "improvement" of subgrade soils and/or by increasing length or embedment of the MSE reinforcing. In addition to using the conventional engineering analyses specified by AASHTO, the Port has utilized advanced methods of analysis that are more typically used for design of dams impounding reservoirs.

The remainder of this report provides additional technical detail to expand on information provided in this executive summary.

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GEOTECHNICAL SUMMARY REPORT
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1.0 INTRODUCTION

This report provides a summary of the process used for geotechnical site investigations, laboratory testing, and analyses used for design and construction of the Third Runway embankment and MSE walls at Seattle-Tacoma International Airport (STIA).

Since 1998, the Port of Seattle has obtained detailed information on soil and groundwater conditions at the site of the proposed Third Runway. This information has been incorporated into the design so that construction will be appropriate for site conditions and conform to applicable building codes and engineering standards. A significant part of this process is to identify seismic hazards and assure that the completed facility meets the seismic performance goals set by the Port.

Geotechnical explorations and tests to identify and measure subsurface soil and groundwater conditions have been accomplished in phases, with intermediate analyses used to evaluate potential stability of the embankment and MSE walls and to identify areas where additional data collection was needed. Methods and results have been extensively reviewed and modified as needed to assure the completed project is safe and will perform as designed.

In several instances, the design approach utilized by the Port significantly exceeds the normal standard of care for transportation infrastructure, and incorporates techniques that are more commonly used for earthen dams. Clearly, performance of the Third Runway project is not as critical as a dam would be from the perspective of safeguarding human life. However, the Port of Seattle recognizes the project is a significant engineering structure, and the Port has utilized sophisticated engineering methods in recognition of the project location adjacent to sensitive and valued surface water resources, and the local community.

The purpose of this geotechnical summary report is to provide the US Army Corps of Engineers (Corps) with documentation of the geotechnical design process that has occurred, and the work in progress, which will lead to completion of design for the embankment and MSE walls.

later in this report. (Note that a companion summary prepared for the Corps, provides additional detail on the hydrogeologic analyses of the Third Runway and adjacent wetlands and creeks; see Hart Crowser 2001l).

1.2 Embankment and MSE Wall Design Team

The Port of Seattle design team for the Third Runway embankment and MSE walls includes internationally recognized engineering firms and a distinguished independent review board. Figure 2 presents an organization chart for the project.

HNTB Corporation is the engineering project manager and civil engineer for the Third Runway project. In business since 1914, HNTB provides engineering and architectural design, planning and construction management for major transportation infrastructure projects. Recent airport experience includes major airport expansion and renovation projects at George Bush Intercontinental Airport in Houston, Midway Airport in Chicago, and Dulles international Airport near Washington DC.

HNTB has selected the Reinforced Earth Company (RECo) to design the MSE walls for the Third Runway project, and Hart Crowser Inc. to provide geotechnical engineering services.

- RECo was chosen as MSE wall designer for the Port of Seattle since they have more extensive experience with design and construction of high MSE walls than anyone else in the world. RECo has designed and successfully constructed more than twenty thousand MSE walls (FHWA 2001), including 12 that are more than 90 feet high, and have been successfully constructed. RECo designed two MSE walls that were built to about the same height as the maximum proposed wall height at SeaTac: a 137-foot-high wall built in 1979 in South Africa and a 133-foot-high wall built in Hong Kong in 1993. These walls were successfully constructed and have preformed well for some time.

- Hart Crowser Inc. is a local geotechnical engineering firm with more than 25 years experience in the Seattle area. Hart Crowser has been lead geotechnical engineer on major infrastructure projects such as the US Navy Home Port in Everett, WA and high-rise buildings in downtown Seattle, such as the Millennium Tower. Hart Crowser has been responsible for stability analyses for the right abutment at Mud Mountain Dam for the Corps of Engineers, Cedar Embankment at Chester Morse Lake for the Seattle Water Department, as well as major tailings embankments for the mining industry.

Hart Crowser has been responsible for design of MSE reinforced slopes that have been successfully constructed up to 150 feet in height.

Hart Crowser has retained expert subconsultants from the University of Washington and elsewhere to provide special geotechnical assistance on the Third Runway design team. These experts include Professor Robert Holtz, PhD, P.E., an internationally recognized MSE expert; and Professor Steve Kramer, PhD, P.E., an expert in earthquake engineering. Other expert subconsultants utilized for the Third Runway Project including Professor Pedro Arduino, University of Washington, for assistance in computer modeling; and Dr. John Hughes who is a specialist in *in situ* testing using the soil pressure meter. Specialty testing firms were also used to assist in geophysics (GeoRecon International); cone penetrometer testing (Northwest Cone); and drilling for soil sampling and installation of monitoring wells (Holt Drilling).

1.3 Embankment Technical Review Board (ETRB)

HNTB has retained the services of an internationally recognized group of eminent engineers to form a special technical review board, to provide independent technical review for the Third Runway project. Detailed resumes for the board members have been submitted to the Corps as part of the record for the 404 permit process. The board members include:

Dr. James K. Mitchell, P.E., is a University Distinguished Professor Emeritus at the Virginia Polytechnic Institute and State University and former Chairman of the Civil Engineering Department at the University of California, Berkeley. Professor Mitchell is an expert in soil behavior, ground improvement, and earth reinforcement.

Dr. I.M. Idriss, P.E., is Professor of Civil Engineering at the University of California at Davis. Professor Idriss is a recognized authority on earthquake engineering and on seismic performance of embankments and other soil structures.

Dr. Barry Christopher, P.E., is an independent geotechnical engineering consultant and internationally recognized expert in MSE wall design, construction, and performance.

The Port's Technical Review Board is coordinated by **Mr. Peter Douglass, P.E.** Mr. Douglass is an independent geotechnical consultant who has earned advanced degrees in civil engineering and geology. Mr. Douglass has more than 30 years of geotechnical engineering experience in the Seattle area as well as around the world.

The ETRB has been given the engineering data, design reports, results of calculations, and MSE design plans to date, for review and comment. Some or all of the members of the Board met with the Port's design team six times in the period November 2000 to October 2001, and have participated in several conference calls to provide expert input to the ongoing site explorations, analyses and design.

Working closely with the Port's design team, the ETRB has developed a good understanding of geotechnical issues pertinent to design and construction of the Third Runway. Drawing on their extensive expertise with analysis of earthquakes, soil reinforcement, and soil behavior, the Board has provided recommendations for improving the accuracy of analyses by the design team and use of sophisticated engineering methods to confirm results. Equally important is the practical knowledge and understanding the ETRB has from their extensive experience in construction and performance evaluations of large embankments and MSE walls around the world.

1.4 Other Independent Review Consultants

During preliminary stages of design, the Port of Seattle reviewed eight different types of retaining wall and more than 60 wall/slope combinations before selecting the proposed MSE wall configuration (HNTB, Hart Crowser, and Parametrix 1999). The evaluation of alternatives by the Port's design team was independently reviewed by qualified geotechnical engineers at Shannon & Wilson Inc. Shannon & Wilson is a highly regarded local engineering firm that is **not** part of the Port's Third Runway design team.

Shannon & Wilson concluded that the proposed MSE retaining walls are "most appropriate" for this site. Their findings were documented by letter and submitted to the Corps of Engineers as part of the public record for the Section 404 permit process.

The Port also obtained technical assistance in developing the scope for MSE wall design from Mr. Tony Allen, P.E. Mr. Allen is the State Geotechnical Engineer for the Washington State Department of Transportation (WSDOT). He has participated extensively in developing national standards for MSE design through his work with the American Association of State highway and Transportation Engineers (AASHTO).

AASHTO has developed a rigorous code for design of MSE walls based on the experience of numerous state transportation agencies, other engineering organizations, and research by the Federal Highway Administration (FHWA). This code is part of AASHTO's "Standard Specifications for Highway Bridges" and is the standard of the industry for design of MSE walls. The current version of is presented in the 16th edition, 1996, which has been updated with interim addenda through 2000 (AASHTO 1996-2000). Reference to the AASHTO code in this report indicates the provisions of the 1996 edition with inclusion of the interim addenda through 2000 (which is the most current addendum).

Based in part on recommendations from Tony Allen, the Port is designing the Third Runway MSE walls in accordance with the AASHTO code. Mr. Allen also recommended the Port utilize another industry standard, the HiTec Protocol, another industry standard as part of checking the MSE wall designs for the Third Runway project, and this is being done by HNTB.

2.0 GEOTECHNICAL SUMMARY

This section of the report provides a discussion of the geotechnical work completed and current progress of design of the Third Runway embankment and MSE walls that is discussed later in this report. Engineering aspects of the project that were described in a previous report to the Corps (Hart Crowser 1999c) are substantially unchanged.

This report summarizes the performance standards, and codes and standards that guide the geotechnical design process for the Third Runway project. This summary also describes the extensive soil explorations, tests and analyses that have been completed and/or are ongoing as part of final design. This report notes where additional geotechnical information is documented in the reports and technical memoranda that are listed at the end of this report, along with other references.

2.1 Performance Standards for Geotechnical Design

The geotechnical design for the Third Runway project conforms to several types of design performance standards. These include satisfaction of numerical requirements in the AASHTO code for design of MSE walls, as well as the readily understood seismic performance goals that were outlined in the executive summary to this report.

The Port has used a great deal of care to identify applicable design requirements and to verify that its design satisfies all the requirements of the AASHTO code. The Port has also addressed other engineering methods and criteria as a check on its design. In particular, the Port has accomplished deformation modeling with sophisticated computer modeling tools (programs referred to as QUAD4 and FLAC, that are described later in this report). Deformation models are important because they provide "real world" estimates of performance (such as "how far will a wall move during an earthquake?"). The deformation models used by the Port also provide a detailed picture of how stresses in the embankment and the MSE walls will change during earthquake shaking.

The approach used by the Port enables verification that not only does the design satisfy the code requirements, but also that estimated movements of the embankment and MSE walls are acceptable.

The Port has designed the Third Runway embankment and MSE walls to meet the following seismic performance requirements:

- MSE walls and fill will remain stable during and following the design level of earthquake shaking (average return interval of 475 years). Some deformations and/or cosmetic damage to the walls are acceptable provided the stresses are not large enough to cause failure.
- There will be no wetland or creek impacts from the embankment or MSE walls due to design level earthquake shaking. Movement will be limited to prevent soil sloughing or release of water that would impact surface water resources adjacent to the airfield.
- There will be no runway operational impacts due to the movement of the embankment slopes or MSE walls subject to the design level of earthquake shaking.

Note that the third performance criterion is specific to the embankment slopes and walls nearest to Miller Creek and adjacent wetlands. Potential effects of liquefaction on pavement within the interior part of the airfield have not been completed as part of the present study.

The design team is able to modify design of the subgrade improvements, MSE reinforcing, and/or the embankment materials and compare the estimated amounts of deformation for representative areas of the project, by the analyses detailed in this report. Seismic deformations analyzed to date for the final design configuration are typically well under a foot, and in some cases up to several feet, based on two independent types of analysis (FLAC and Newmark analyses, see Section 4.2 of this report). Rather than specify a single value for maximum allowable deformation, the design team is reviewing the results of the analyses to assess whether estimated deformations for different areas meet the performance criteria above. For comparison, allowable deformation of up to about three feet is commonly considered acceptable for slopes and earth embankments (ASCE 1983 and Seed 1979).

Finally, it is notable that the Port's design team considered embankment and wall performance over a wide range of circumstances. For instance, the Port checked and verified that the MSE reinforcing stress and deformation levels would still be acceptable if the design level earthquake happened after the reinforcing strength was reduced by the calculated corrosion loss corresponding to a 100-year service life. This combination of the assumed long-term corrosion loss prior to occurrence of the design earthquake is an example of the Port's conservative approach to design.

2.2 Codes and Standards

Design of the Third Runway is covered by the Washington State regulations covering the practice of Professional Engineering (Chapter 18.43 RCW). The senior engineers supervising the work described in this report are Professional Engineers, licensed by the State of Washington, employed by experienced engineering firms such as Hart Crowser, HNTB, and RECo.

The Port's design team reviewed applicable engineering codes and standards, and decided to design and construct the Third Runway MSE walls in accordance with the current edition of the AASHTO code and its interim updates. (AASHTO 1996-2000) and by reference the FHWA standards on MSE walls (FHWA 1997). This decision was based on research contacts with other organizations and companies designing and/or involved with construction of MSE walls, including Professor Robert Holtz, University of Washington; Mr. Tony Allen, WSDOT; and Mr. James (Mickey) McGee, Georgia DOT).

In accomplishing our work, the Port's design team has also referred to other standards of practice for engineering works, such as the engineering manuals developed by the U.S. Army Corps of Engineers (EM 1110-2-2502, EM 1110-2-1913, and ER 1110-2-1806). Geotechnical design work for the Third Runway is similar to what the Corps would require for design of MSE walls and earth embankments (levees), as is also discussed later in this report.

Historically, safety of earth structures such as embankment slopes and retaining walls has been evaluated by stability analyses, using "factors of safety" to assess adequacy of the design relative to the loads expected during the lifetime of the structure. In its simplest form, a "factor of safety" is the ratio of the forces tending to maintain stability divided by the forces tending to cause instability. The AASHTO code (and other standards such as Corps documents EM 1110-2-2502, EM 1110-2-1913, and ER 1110-2-1806) specifies target factors of safety that the design must achieve for specific methods of analysis, and/or goals of analysis where alternative methods of analysis are determined by site-specific conditions.

The Port's geotechnical design procedures and resultant Factor of Safety for each specific analysis meet all AASHTO criteria, and are consistent with procedures used by the Corps (EM 1110-2-2502; EM 1110-2-1913; and ER 1110-2-1806) for design of retaining walls and earth embankments for levees, (Corps 1989, 1995, and 2000). The Port's design significantly exceeds AASHTO requirements by including sophisticated deformation analyses and independent peer review input from the ETRB and others.

HNTB is using the "HiTec Protocol" as a guide for their independent check on RECo's design. The HiTec Protocol (CERF 1998) was developed by the Civil Engineering Research Foundation, an affiliate of the American Society of Civil Engineers, working in conjunction with FHWA and various state departments of transportation. Use of this protocol to check the design documents provides verification that the design includes all the elements found necessary for MSE walls to meet criteria developed by FHWA and the states.

2.3 Subsurface Explorations and Tests

Subsurface exploration and testing to determine soil and groundwater conditions affecting Third Runway design have been underway since the environmental review process for the project in the mid-1990s. The Port has used a phased approach to collect information for different parts of the site, with additional explorations accomplished as needed to better define conditions in particular areas. This report describes how 218 soil borings, 156 test pits, and other explorations have been used to identify and document soil and groundwater conditions; as the basis to assess environmental impacts and for design of the Third Runway.

Initially the subsurface exploration and test program accomplished by the Port of Seattle was based on local geotechnical experience and the results of initial observations. Existing mapped soils information was supplemented with soil borings and test pits to define baseline conditions for environmental review (FAA 1996 and 1997 and AGI 1996).

Additional explorations and tests were accomplished in specific areas to provide detailed information for related projects, conceptual design of the runway, and on-site borrow areas (CivilTech 1997, HWA Geosciences 1998, AGI 1998, and Hart Crowser 1998 and 1999a). A detailed description of the project was prepared for the Corps (Hart Crowser 1999c) with an accompanying subsurface conditions data report (Hart Crowser 1999b).

Subsurface information was subsequently obtained as part of a phased investigation that first addressed the locations for the three proposed MSE walls

(Hart Crowser 2000b (North or NSA Wall), 2000d (South Wall), and 2000f (West Wall)).

The type and frequency of subsequent explorations and testing were determined from assessment of the project's geologic environment; the extent of variation observed in initial test results; and additional data needs for specific parts of project design (Hart Crowser 2000j and 2001b and Appendix C of Hart Crowser 2001j). The design team had input from the ETRB in identifying the need for the final explorations and tests.

Field and laboratory work was accomplished in general accordance with standards developed by the American Society for Testing and Materials (see ASTM 2001 for current details). Table 1 summarizes the subsurface explorations that were accomplished; Table 2 lists the laboratory analyses that were used.

2.4 Seismic Basis of Design

The Port's design team made a considerable effort to select a reasonable basis of design to evaluate seismic effects on the Third Runway embankment and MSE walls. After review of procedures used for seismic design of other major structures and facilities, the Port of Seattle design team selected a probability-based approach that utilizes measurements from previous earthquakes throughout the Pacific-Northwest region, to predict the level of future seismic shaking at Sea-Tac (Hart Crowser 2000e and 2001a).

The design team completed a site-specific probabilistic seismic hazard assessment (PSHA) that utilizes current attenuation relationships and earthquake data, which have been peer-reviewed and are extensively used in Seattle and elsewhere for design of bridges and major buildings. The PSHA produced a relationship between the peak seismic acceleration and average recurrence period specific to the project site.

The Port of Seattle is basing design on the level of seismic shaking that has a 10 percent probability of exceedence in 50 years and an average return period of 475 years. Design using the 475-year seismic level of shaking is reasonable for the Third Runway facility. This level of event is commonly used for transportation facilities of normal importance, such as highway bridges and public buildings. While the Third Runway embankment and retaining walls are significant structures; they are not essential to airport operations. Potential damage to the Third Runway that might occur from an earthquake larger than the basis of design event would be similar to what might occur for other transportation facilities that use similar design standards. There is no risk of catastrophic loss of life due to seismic effects on the Third Runway, such as might result from failure of a dam or nuclear power plant.

Design for the level of shaking selected for the Third Runway is consistent with the approach that has been used for other major construction at STIA (e.g., the current South Terminal Expansion Project—a building that has thousands of people in it every day). The Third Runway design specifically addresses both the amount of movement that will occur as well as the stresses that will develop within the embankment and MSE walls as a result of earthquake shaking.

The design included development of several ground motions that were used in progressively more sophisticated analysis as design has proceeded. This aspect of design includes expert input from the University of Washington and has been closely scrutinized by the ETRB. Final design includes evaluation of stability and deformation for three ground motions (acceleration time history records) that were selected to represent the range of shaking obtained from the PSHA, as well as a ground motion from a deterministic source (the Seattle Fault) corresponding to a 475-year return period.

2.5 Stability and Deformation Analyses

The basic design approach for the Third Runway embankment and retaining walls is to use limit equilibrium stability analyses to determine the extent of subgrade improvement needed to meet minimum target factors of safety for different load conditions. For the MSE walls, the analyses included both global stability (to evaluate potential failure surfaces that extend behind and below the MSE reinforcing) as well as compound stability (to evaluate potential failure surfaces that pass through the reinforced soil zone). Reinforcement thickness, length, and/or embedment were increased as needed to meet target factors of safety. As a final check, deformation analyses are being used to verify the design will meet the Port's performance standards.

Limit equilibrium stability analyses were used to assess stability of the embankment including its MSE reinforced wall sections. Representative cross sections of the Third Runway embankment and retaining walls were analyzed for stability under the following load conditions:

- End of construction;
- Steady state;
- Seismic; and
- Post-liquefaction.

Cross sections were selected for analysis to represent the fill height, shape or geometry of the embankment/wall cross section, and the range in observed subsurface conditions. In most cases, our analyses showed that stability was more influenced by the strength of the existing subgrade soils, than the strength of the embankment or MSE fills, and "subgrade improvement" was needed to meet target factors of safety in specific areas (as described in Hart Crowser 2000 g). In some cases, increased length or depth of embedment of the MSE reinforcement was needed to meet target factor of safety (Hart Crowser 2000m, 2001g, and 2001k).

Two types of deformation analysis are being used to independently check performance of the Third Runway embankment and MSE walls.

- One method uses a finite difference program (FLAC) to calculate changes in stress and strain to simulate construction, and effects of the acceleration time history for seismic shaking. This analysis also considers the effect of reduced soil strength and stiffness due to liquefaction and cyclic loading.
- The other method uses a finite element program (QUAD4) to calculate accelerations throughout the embankment and MSE walls, and calculates displacements that occur when acceleration exceeds the yield acceleration for different parts of the embankment, using the Newmark method.

2.6 MSE Wall Design

MSE walls for the Third Runway are being designed to satisfy the following criteria:

1) Design requirements in the AASHTO code for MSE walls (AASHTO 1996-2000);

2) RECo in-house criteria, which include results of both theoretical and empirical methods of analysis, and performance criteria based on construction of similar walls;

3) Verification that RECo's design meets the target factor of safety criteria for both global and compound stability (as described above);

4) Verification that the proposed design will result in acceptable deformations for the design level of seismic shaking; and

5) Other functional and aesthetic requirements established by the Port.

All the analyses of the MSE sections were based on the calculated reinforcing section at the end of a 100-year performance period (i.e., including allowance for corrosion).

Design of the MSE walls is well along, including submittal of 30 percent draft plans, calculations, and quality assurance documents by RECo, and review by the rest of the design team (HNTB 2001).

2.7 Geotechnical Aspects of Construction

The culmination of the tests and analyses described in this report is the production of construction contract documents that show how the embankment and MSE walls must be constructed to achieve the design expectations. The limits of subgrade improvement, which were selected by design to meet target factor of safety in the stability analyses, will be shown on construction plans with accompanying Specifications that include detailed information on the quality of construction required.

Within the areas where subgrade improvements are needed, the Port plans to excavate the problematic soils (generally loose saturated sands, soft to stiff silt and clay soils, and peat) and replace them with densely compacted select fill. The Port evaluated nine alternative methods of subgrade improvement (Hart Crowser 2000g) and selected removal and replacement of problem soils (sometimes referred to as overexcavation and replacement) as the most desirable alternative because it will provide the highest level of ground improvement and the best quality control among the available alternatives.

The construction contract documents for the Third Runway project also specify the length, thickness, spacing, and arrangement of steel reinforcing strips that support the MSE walls, and the allowable soil types and compaction requirements needed to assure the constructed embankment meets the criteria used to achieve the target factors of safety and anticipated deformations.

The remainder of this report presents information on the soil and groundwater data used for design, the methods of geotechnical analyses that were used, and input of geotechnical input to the MSE design. Section 6.0 provides additional detail on geotechnical aspects of the proposed construction process.

3.0 SOIL AND GROUNDWATER DATA USED FOR DESIGN

This section of the report provides a summary of the methods of investigation used to assess subsurface conditions at the project site and an overview of geologic conditions that influence design. The final part of this section discusses selection of representative soil properties for use in the stability analyses.

3.1 Subsurface Explorations and Soil Tests

A large number of both conventional and special subsurface explorations have been accomplished to obtain geotechnical engineering parameters for the Third Runway project. These explorations are summarized in Table 1, and shown on a Site and Exploration Plan, Plates 1, 2 and 3, included at the back of this report.

Preliminary Explorations

As part of the environmental impact assessment and initial planning for the Third Runway project, the Port of Seattle accomplished 91 soil borings and a number of test pits and hand auger explorations (AGI 1996 and 1998). The borings were typically accomplished with hollow-stem auger or mud rotary drilling techniques, using the Standard Penetration Test (SPT, per ASTM D 1586) to collect soil samples and information on soil density or consistency. (Note throughout this report, applicable procedures developed by the American Society for Testing and Materials, are referred to simply by their test method designation. See ASTM 2001 for complete details). Nineteen of the initial borings were completed as groundwater observation wells.

Geotechnical Design Phase Explorations

During the geotechnical design phase, Hart Crowser completed an additional 127 hollow-stem auger borings, again using SPT to collect soil samples. At some of these boring locations, parallel borings were also drilled to obtain thin wall (Shelby) tube samples for laboratory testing. (These additional borings were not counted or numbered separately because they were merely to collect additional undisturbed soils samples at specific locations where the primary borings had been used to identify the soil strata).

Hart Crowser completed 65 of the design phase explorations as groundwater monitoring wells. All monitoring well locations were surveyed and groundwater level observations were recorded over a period of 1 to 3 years.

In addition to the borings, the main geotechnical design phase included 122 test pits excavated with a track-hoe, and numerous shallow hand auger explorations. Cone penetrometer test (CPT) soundings were completed at 48 locations to obtain information on stratigraphy, strength and stiffness of fine-grained soils (primarily silt and clay), as well as soil pore pressure parameters.

Additional Special Field Tests

During the design phase, a number of other special field tests were accomplished to better define subsurface conditions. These tests included:

- Two types of infiltration tests were used to evaluate effects of construction on groundwater, and stormwater infiltration. The tests included ring infiltrometer tests accomplished with a double-ring apparatus in test pits, and falling head infiltration tests accomplished in well casings;
- Vane shear tests were accomplished to obtain *in situ* measurements of undrained and remolded strength of clay and peat soils;
- Pressuremeter tests were used to obtain *in situ* stress-strain data, to enable calculation of soil shear modulus; and
- Down-hole compressional and shear wave velocity measurements were completed in a 100-foot-deep boring at each MSE wall location.

The last two of these special tests were accomplished specifically to obtain soil parameters for accurate modeling of MSE wall performance as discussed later in this report.

Soil samples were typically obtained in each boring at 2.5- to 5-foot-depth intervals. Each visible soil strata was individually sampled in the test pits and hand auger explorations.

Soil samples were visually classified in the field, in general accordance with the Standard Practice for Description and Identification of Soils (ASTM D 2488; see Figure 3). The classification is based on describing the density or consistency of the soil, moisture content, color, and gradation. Where present, organic material or debris was also noted.

Results of the explorations and field tests are presented in data reports, which are listed in the bibliography at the end of this report. (See for instance: AGI 1996 and 1998, CivilTech 1997 and 1998, HWA Geosciences 1998, and Hart Crowser 1999a, 1999b, 2000b, 2000d, 2000f, 2000j, 2000n, 2001b, and 2001j).

Laboratory Testing

Soil samples were delivered to Hart Crowser's laboratory in Seattle and logged into the sample tracking system. Hart Crowser's laboratory is currently certified by the Army Corps of Engineers to accomplish geotechnical testing on Corps' projects.

Upon receipt in the laboratory, the visual classification prepared in the field was checked under more controlled conditions, and samples were selected for testing. Moisture content was determined for most of the samples, and representative samples were selected for tests such as plasticity, gradation, strength, or compressibility.

Testing was accomplished in general accordance with the ASTM methods that are listed in Table 2.

All laboratory test results were reviewed by a Hart Crowser engineer, who prepared the data reports, summarized information for specific soil units, and compared results with properties estimated or reported by others for similar soils. In-house technical memoranda were prepared in some cases to summarize and document specific test results, (e.g., Hart Crowser 2001i and Appendix D in Hart Crowser 2000k).

3.2 Geologic Overview

For purposes of designing the Third Runway embankment and retaining walls, site geologic conditions can be divided into three areas of interest: a) relatively soft or loose surficial soils; b) dense or hard glacially overridden soils; and c) location and flow of shallow groundwater. Bedrock is quite deep and is not an explicit part of design except as it relates to potential earthquakes (discussed later).

Surficial Soils

Soils underlying the proposed Third Runway embankment typically consist of up to about 20 feet of loose to medium dense sandy soil with varying amounts of silt or clay, interbedded (or overlain) with soft to stiff sandy silt, clay, peat, and fill. Figure 3 summarizes the system we used to classify these soils and serves as a key to the exploration logs presented in other Third Runway project reports (Hart Crowser 1999a, 1999b, 2000b, 2000d, 2000f, 2000j, 2000n, 2001b, and 2001j). The surficial soils generally present at the Third Runway site included the following components, although not all these types are present at all locations.

Topsoil. Topsoil, consisting of a loose mixture of silt and sand with roots and other organic material, was intermittently encountered in our explorations, ranging from about 1/2 to 1 foot thick, where it was encountered.

Pre-Construction Fill. Existing fill, consisting of a loose to medium dense, variable mixture of silty or clayey sand and gravel, was encountered in some locations, typically associated with prior site use, including paved streets and residential housing. Fill is generally absent in the low-lying portions of the site adjacent to the creeks and wetlands. Most of the fill is less than 1 foot thick but occasionally varies up to 10 or more feet in thickness. The density and granular nature of the fill materials resembles the recessional outwash deposits described below, and the fill is sometimes difficult to distinguish from the outwash.

Alluvial Deposits Consisting of Interlayered Silt, Clay, Sand, and Peat. Alluvial deposits are sediments associated with Miller Creek or Walker Creek. These soils occur mainly in the low-lying areas to depths of up to about 15 feet.

The consistencies of the clay and silt deposits vary widely from soft to stiff or hard, and these soils generally contain sand fractions ranging up to about 30 percent by weight. Typically these clays and silts are low in plasticity, see Figure 4.

The alluvial sands are generally loose to medium dense, and range from non-silty to very silty or clayey (i.e., up to about 50 percent fines [particle sizes less than 0.074 mm]).

Peat was encountered in portions of some wetlands located near the west central part of the embankment, and in the north part of the embankment, both areas near to Miller Creek. Both surficial and shallow buried peat deposits were encountered. Buried deposits tend to be medium stiff to stiff, whereas the surficial peat exhibited consistencies in the very soft to soft range. Buried peat deposits were encountered at depths ranging from about 3 to 10 feet and varied in thickness between about 1 to 6 feet. Peat deposits near the ground surface varied in thickness between a few inches and about 2 feet.

Colluvium and Recessional Outwash. These soils generally consist of medium dense to dense, slightly silty to silty, slightly gravelly to gravelly sand.

Colluvium refers to soils that have been displaced by erosion or other natural processes on slopes subsequent to their original deposition. Recessional outwash overlies the glacial till, and overlies the advance outwash where the glacial till has been eroded. Thickness of the colluvium and recessional deposits varies over the site, but is generally less than 20 feet. These deposits vary in gradation over relatively short distances, and are intermittent or absent where alluvial materials are located.

Glacially Overridden Soils

Glacial Till. Glacial till soils observed at the site consist of dense to very dense, slightly gravelly to gravelly, silty to very silty sand. In general, glacial till differs from the overlying recessional soils by having a higher silt content and much higher density.

Glacial till is generally encountered within 10 to 20 feet of the ground surface, on the upper (eastern) part of west-facing slope on the west side of the existing airfield. The glacial till was not encountered in the explorations in downslope areas to the west, where the explorations terminated in advance soils. Springs and seeps occur along the western edge of the glacial till due to both perched water and interflow above the glacial till horizon as well as groundwater seepage from the aquifer in the underlying advance sands.

Advance Deposits. Underlying the glacial till are soils that were deposited in advance of glaciation and subsequently overridden. These advance soil deposits consist of dense to very dense, slightly silty, slightly gravelly to gravelly sand, with local interbeds of very stiff to hard silty or clayey soils. In general, but not always, the advance deposits can be distinguished from the glacial till by lower silt or clay content.

Groundwater

Shallow groundwater flows through the fill, colluvium, and alluvial soils, including seepage perched on the glacial till and on silty or clayey zones of the soils noted above. Seepage varies seasonally.

Shallow groundwater within the advance outwash soils and perched water in the overlying soil units combines to produce the "Shallow Regional Aquifer" in low lying areas adjacent to Miller Creek and Walker Creek. The Port has been monitoring water levels in this area for several years (1994 to date for some of the wells installed for the Third Runway), to assess the potential effect of embankment construction on base flow to these creeks and their tributary wetlands.

Shallow groundwater elevation contour maps have been developed and presented in several reports dealing with different parts of the project (Hart Crowser 1999c, 2000b, 2000f, and 2001j).

STIA also overlies two other aquifers that are considerably deeper and are used for water supply (AGI 1996).

An accompanying memorandum prepared for the Corps (Hart Crowser 2001l) discusses hydrogeology of the region and modeling to evaluate the effect of the Third Runway embankment on groundwater recharge and surface water hydrology.

3.3 Selection of Soil Parameters for Use in Analyses

The field and laboratory test results were reviewed to determine appropriate values for input to the geotechnical engineering analyses. Conservative test values were typically selected for use in the stability analyses, based on inspection of the range of data collected. Table 3 shows values of soil parameters used for different soil units in the stability analyses. Additional information on parameters used in the deformation analyses is presented in Hart Crowser (2000i).

Parameter values used in the geotechnical analyses were conservatively selected based on the range of results measured. Examples of this are illustrated on the figures described below.

- Figure 5 shows the range of drained friction angles measured over the range of embankment confining pressures (up to about 12 tons per square foot). Values were typically well above the 32 degree value used in analyses (see Table 3) especially at lower confining pressures.
- Figure 6 shows the undrained strength ratio (undrained shear strength normalized with respect to effective overburden pressure) used in our analyses, compared to undrained strength test results for the Third Runway project, and values reported by others for various soil types (Ladd 1986).
- Figure 7 shows the range in values for coefficient of consolidation, c_v, measured for silt and clay soils encountered in our borings. The design value used for analysis of pore pressures at the end of construction (EOC) is below most of the measured values, which results in conservative estimates of the rate of consolidation.
- Where possible, laboratory test measurements for parameters such as undrained strength, fines content, and consolidation coefficient were compared to field test measurements with the CPT, and field exploration data were used to define the areas where specific soils parameters were applicable.

Results of the laboratory tests are presented in data reports and memoranda, (See for instance: AGI 1996 and 1998, CivilTech 1997 and 1998, HWA

Geosciences 1998, and Hart Crowser 1999a, 1999b, 2000b, 2000d, 2000f, 2000j, 2000n, 2001b, and 2001j).

4.0 METHODS OF GEOTECHNICAL ANALYSIS

A number of geotechnical analyses have been completed for design of the Third Runway embankment and retaining walls, specifically including 1) stability of the embankment slopes and MSE walls; and 2) deformation, or movement, of the slopes and MSE walls, for both steady state and seismic conditions. These two types of analyses are discussed in this report because they pertain directly to the question of potential off-site impacts that is of interest to the Corps. (Other types of analyses such as settlement of the embankment, or infiltration and groundwater effects of the embankment, are discussed in Hart Crowser 2000g, Appendix C in Hart Crowser 2000o, and Hart Crowser 2001l).

4.1 Stability Analyses

Limit equilibrium stability analyses were used to evaluate design of the embankment fill, to design the extent of subgrade improvements, and to check the MSE wall reinforced zones. The AASHTO code specifies that both static and seismic analyses should be accomplished, and specifies target factors of safety that should be achieved. (Note, the Port used the same approach for "end of construction" analyses, which is not specified by AASHTO, but was appropriate to include for some soil conditions at the site.)

Table 4 lists the target factors of safety for limit equilibrium analyses used for the Third Runway. For comparison, Table 4 also shows the target factor of safety criteria used by the Corps of Engineers for comparable analyses of levees, as presented in EM 1110-2-1913 (Corps 2000).

Hart Crowser primarily used the program SLOPE/W (Geo-Slope 1998) for limit equilibrium analyses. We checked its performance by comparing analyses on specific MSE embankment sections to analyses using another well-documented program: UTEXAS3 (Hart Crowser 2001b).

To date 30 representative cross sections of the Third Runway embankment and retaining walls were analyzed using limit equilibrium analyses. Additional sections may be selected for further analysis depending on work in progress. Hart Crowser analyzed five to eight sections for each of the three MSE walls, and eight other sections to represent different areas of the 2H:1V embankment slopes. The sections used for analyses were selected to evaluate the range in subgrade conditions and embankment/wall geometries for the Third Runway project as a whole.

Figure 8 shows how soil strata are depicted for stability analysis of a typical embankment slope that is being checked for a potential failure surface; dozens of potential failure surfaces were analyzed for each cross section. In each case where the result did not meet or exceed the target factor of safety, the design was modified and the analysis was repeated until the target was met.

The analysis cases used for the Third Runway are described below:

- End of Construction (EOC) refers to the analysis of stability related to build-up of excess pore pressures in fine-grained soils in the embankment fill or subgrade, as construction proceeds. In cases where analyses using "worst case" unconsolidated, undrained (UU) strength parameters for foundation soils produced factor of safety values below the target level, stability was reanalyzed using more realistic partially consolidated strength properties. Our partially consolidated analysis used a spreadsheet model to calculate changes in subgrade strength due to pore pressure development and dissipation. Pore pressures were calculated as a function of the construction fill placement rate and measured thickness of silt and clay subgrade soils in different parts of the site. Target factor of safety for the EOC condition for MSE walls is 1.3.

- EOC analyses also included analysis of the range of excess pore pressures observed in previous construction with fine-grained embankment fill. Analysis of the Third Runway embankment for the pending Phase 5 construction with the maximum pore pressure values reported in the literature for embankments more than 200 feet high produced factors of safety of 1.3 or greater (Clough and Snyder 1966). We anticipate similar results would be achieved for future stages of embankment design. Hart Crowser is also using EOC analyses to check temporary cut slopes for the subgrade improvement excavations.

- Steady-state refers to the stability of the embankment under long-term conditions (i.e., with gravity loading but not seismic). Soil strength values used in these limit equilibrium analyses included the effect of strength gain due to consolidation from embankment construction, so a higher factor of safety is expected for some soils compared to the EOC condition. AASHTO allows the factor of safety for this condition to be either 1.3 or 1.5 depending on importance of the wall. Target factor of safety for MSE walls subject to steady state conditions for the Third Runway project is 1.5.

- Seismic stability analyses consisted of pseudo-static limit equilibrium type analyses, to conform to AASHTO criteria (AASHTO 1996-2000). AASHTO requires the target factor of safety for seismic conditions to be at least 1.1, which is the value used by the Port. The seismic hazard analysis used to obtain representative ground motions is described below in Section 4.2, (see also Hart Crowser 1999d, 2000e, and 2001a).

- For preliminary analyses, Hart Crowser used a value of 0.16 for the pseudo-static horizontal load vector in the limit equilibrium analyses. The initial value of 0.16 used for the pseudo-static load was half the peak horizontal acceleration (PHA) obtained from the averaged results of one-dimensional ground motion analysis (PROSHAKE) for embankment heights of 40 and 160 feet. Final design used half the PHA from the two-dimensional QUAD4 analyses discussed below, where this value was greater than 0.16.

  Hart Crowser used the consolidated undrained soil strength for cohesive soils (silts/clays) for the pseudo-static stability analysis (and the FLAC analysis discussed below) to account for the combined effect of both strength increase due to higher strain rate and potential strength reduction due to cyclic shaking.

  Minimum target factor of safety for the seismic (pseudo-static) stability specified by AASHTO is 1.1. For some areas, the analyses produced factors of safety between 1.0 and 1.1 for small potential failure surfaces near the toe of the fill or shallow raveling type zones on the upper surface of embankment slopes. In these instances, Hart Crowser verified the target factor of safety was met for deeper potential failure surfaces and relied on deformation analyses discussed below to verify there was no potential for progressive failure (i.e., potential for shallow raveling to lead to more extensive instability).

- Post-liquefaction stability analyses utilize reduced soil strength to represent the strength loss that occurs in some soils when excess pore pressures develop due to seismic shaking. Details of the liquefaction trigger analysis and estimation of post-liquefaction residual strength are discussed below in Section 4.3 (also see Hart Crowser 2001d). The target factor of safety for the post-liquefaction residual strength analyses was 1.1.

The limit equilibrium analyses were accomplished for both global stability and compound stability for the MSE walls. "Global stability" refers to analysis of potential instability due to failures below and behind the reinforced zone of the MSE walls, as shown on Figure 9. "Compound stability" refers to analysis of potential stability that extends through the reinforced zone as well as behind or below it (see Figure 10). In each analysis, a wide range of potential failure surfaces was examined, including circular surfaces, wedge-shaped surfaces, and irregular surfaces.

Limit equilibrium analyses were initially accomplished to estimate the spatial limits of subgrade improvement that might be needed using an assumed geometry for the reinforced zone behind the MSE walls (Hart Crowser 2000g). Additional analyses were accomplished for the 2H:1V embankment (Hart Crowser 2000o) and for the MSE walls using the reinforced zone geometry presented in RECo's 30 percent plans (Hart Crowser 2000m and 2001i). Limit equilibrium analyses for final design are currently in progress. For some of these analyses we are also considering the effect of using different backfill materials with higher strength values to potentially reduce the extent of subgrade improvements for particular sections, while still meeting performance standards.

MSE Wall Design Analyses

Section 5 of this report provides a summary of the MSE design process for the Third Runway; this subsection summarizes conventional limit equilibrium slope stability analyses that were utilized to check and/or modify the MSE design. Other forms of limit equilibrium analyses were also used by RECo for internal design of the reinforced zone for each of the Third Runway MSE walls in accordance with AASHTO code.

Design of MSE walls for the Third Runway is required to satisfy all of the following criteria:

1. Design requirements in the AASHTO code for MSE walls (AASHTO 1996-2000);

2. RECo in-house criteria, which include results of both theoretical and empirical methods of analysis, and performance criteria based on construction of similar walls; and

3. Verification that RECo's design meets the target factor of safety criteria for both global and compound stability (as described above); and

4. Verification that the proposed design will meet acceptable deformation criteria.

Table 5 summarizes geotechnical design requirements for the Third Runway MSE walls (for more detail see Hart Crowser 2000h). As noted above, the final design satisfies the strictest criteria from both RECo and AASHTO.

There is considerable similarity between the Third Runway design based on the AASHTO code requirements and the design criteria used by the Corps of Engineers for design of retaining walls, as presented in the engineering manual EM 1110-2-2502 (Corps 1989). Table 6 shows the Corps design criteria for retaining walls. The Corps criteria are very nearly the same as the Third Runway criteria presented in Table 5, with two minor exceptions:

- AASHTO allows the factor of safety for bearing capacity to be 2.0 on the basis of a detailed geotechnical analysis, while the Corps requires a value of 3.0. Analysis by Hart Crowser indicated the bearing capacity factor of safety for the Third Runway MSE walls exceeds the minimum value specified by the Corps.
- In addition, the sliding analysis specifically for walls on bedrock required by the Corps (see Note 3 in Table 6) is not applicable for the Third Runway, because the Third Runway walls are not founded on bedrock.

Except for the bedrock criterion that is not relevant, the design used for the Third Runway MSE walls meet or exceed comparable criteria used by the Corps (1989).

4.2 Deformation Analyses

Dynamic deformation analyses were used to assess performance of the Third Runway embankment and MSE walls by calculating how much movement would be produced by the design level shaking. The deformation analyses provide an independent check of the adequacy of the subgrade improvements, which were designed using the limit equilibrium analyses.

Two types of deformation model were used: a Newmark analysis and the finite difference model FLAC.

Newmark Analysis

Review by the ETRB identified reliance on pseudo-static analyses as one area where the Port could improve its design over the AASHTO requirements and recommended that a Newmark deformation analysis also be used.

The Newmark analysis method calculates displacements that will occur when the acceleration due to seismic shaking exceeds the level referred to as the yield acceleration (which is the acceleration that would produce a factor of safety of 1.0 in a pseudo-static analysis) (Newmark 1965). For this analysis, Hart Crowser used successive pseudo-static limit equilibrium analyses (accomplished with

Slope/W) to determine the yield accelerations for potential failure surfaces. In all cases we checked 10 or more potential failure surfaces for each of several cross sections. A two-dimensional site response program, QUAD4, was used to calculate seismic acceleration for each of these potential failure masses, using one or more acceleration time histories. Displacements were calculated by double integration of the motion during the times when acceleration produced by the time history exceeds the yield acceleration value.

Figure 11 illustrates a typical distribution of potential failure surfaces for the Newmark analysis of a MSE wall section, and the corresponding tabulated values of the yield acceleration k_y and maximum seismic acceleration k_{max}. We used both direct integration of the time history to estimate deformation, as well as the simplified approach using a k_y/k_{max} ratio as described by Makdisi and Seed (1978), since different magnitudes of deformation were produced by these methods for some of the sections. In most cases evaluated to date, the analysis showed negligible displacements (<0.1 foot). Subgrade improvements are being re-evaluated for two sections that had horizontal displacements of 1 to 2 feet.

Where the Newmark analysis displacements exceeded negligible values, Hart Crowser is accomplishing more detailed deformation analysis using the FLAC program. The Newmark analysis is also being used to check on some embankment sections to assess whether potential shallow surficial sloughing or small zones of potential instability (indicated by the pseudo-static limit equilibrium analysis) could lead to progressive raveling.

FLAC Analysis

The computer modeling program FLAC is being used to evaluate the seismic response and deformation of the Third Runway embankment and MSE walls. FLAC is an advanced tool for seismic analysis that is being used to confirm and supplement the conclusions from the more conventional analyses.

FLAC provides a good means to display results of stress-strain analysis using the finite difference method. The FLAC model helps illustrate the mechanisms of deformation, which generally verify the limit equilibrium analyses. (Lack of consistency between results of the two methods would be an indication of the need for further analysis of a particular section, if this were to occur.)

FLAC has been extensively used by others for dynamic analysis of earth structures, including some comparison of FLAC results with centrifuge models and in some cases with the effects of real earthquakes. Examples in engineering literature include: Inel, Roth, and C. de Rubertis 1993, Lee 1997, Makdisi, Wang, and Edwards 2000, Bathurst and Hatami 1998 and 1999, and Roth et al. 1993.

The Third Runway design team is using FLAC analysis techniques that have been demonstrated effective by research completed at the University of Washington that includes use of FLAC for both static and seismic analyses of MSE wall performance. The University of Washington research demonstrates the reasonableness of FLAC analyses for seismic analysis of MSE walls based on comparison with shaking table and centrifuge test results.

The finite difference mesh used in the FLAC model is "built" incrementally to provide a realistic estimate of stresses and deformations due to the weight of the fill. A "time history" of earthquake motion provides the basis for calculating additional stresses and deformations to assess the effect of design level earthquake shaking on the proposed embankment and MSE walls. The FLAC program provides both graphic and tabulated output, which can be used for further analysis, (for example see Hart Crowser 2000m and 2001g).

Figure 12 shows an example of the maximum horizontal displacement calculated for preliminary analysis of a representative section of the west MSE wall. The displacement contours indicate that the top of the wall would have a permanent displacement of about 10 inches resulting from the earthquake design motion (discussed below). The calculated vertical deformations are much less than the horizontal displacement. Another part of this same analysis provides designers with a tabulation of the maximum stress in the MSE reinforcing strips used in this section (see for example Hart Crowser 2001g).

FLAC model results are used to check predicted deformation vs. performance goals for the MSE walls. As needed, the reinforced zone or the subgrade improvements can be modified and the analysis repeated to see how performance (displacement or stress) is affected. An acceptable design for each section is obtained by comparing the results of both limit equilibrium and deformation models. Use of FLAC enables the Port to estimate wall movement and stresses in the reinforcing for a wide range of conditions from construction through performance in various size earthquake events, a capability that is not equally available from alternative computer models.

The FLAC analyses used for the Third Runway are above and beyond conventional design practice for MSE walls, i.e., the AASHTO code, which only requires pseudo-static analyses, used by the Port. However, the use of deformation-based analyses is gaining wide acceptance because of limitations in other types of analyses. Use of FLAC by the Port's design team provides an increased level of understanding regarding the MSE walls performance both during construction and in service.

4.3 Seismic Basis of Design

Input for both QUAD4 and FLAC is in the form of a record of motion, which is developed from an earthquake acceleration record selected to represent a "design level earthquake." This section discusses the basis for selecting the design level earthquake.

The Third Runway embankment and MSE walls are being designed to perform well during and after earthquake shaking that has a 10 percent probability of exceedence in 50 years, or an average return period interval of once in 475 years. Seismic events of this frequency are commonly used for design of many structures such as commercial buildings and highway bridges. This is the same basis of design return period that the Port of Seattle has used for other significant structures at STIA, such as the South Terminal Expansion Project currently under construction.

The process used to determine the magnitude of the seismic basis of design event began with a Probabilistic Seismic Hazard Assessment (PSHA). The PSHA utilizes thousands of analyses (for different source-site distances, magnitudes, and earthquake characteristics [such as the effects of fault type], and attenuation relationships) to produce a probability based uniform hazard spectra that represents potential earthquake effects on the site (Hart Crowser 1999d, 2000e, and 2001a).

Several ground motions have been utilized for the Third Runway analysis to cover the range of earthquake shaking characteristic of the design level event. These motions, designated A, B, C and D, include one motion that is deterministically based, to specifically assess motion on the most significant local fault, the Seattle Fault.

Initial design analyses used the model PROSHAKE to complete a one-dimensional site response analysis. The average peak horizontal acceleration (PHA) from this analysis was used to provide input to a) the pseudo-static analyses used to evaluate global and compound stability; and b) the MSE design analyses accomplished by RECo. The AASHTO design method includes PHA in a Mononabe Okabe-type analysis for determination of lateral earth pressures.

Subsequent Third Runway design analyses used the program QUAD4 to complete two-dimensional site response analysis for representative embankment and MSE wall sections. The QUAD4 analysis was used to obtain the following:

- Seismic cyclic shear stresses at different locations, to assess potential for liquefaction below or adjacent to the embankment;

- Maximum acceleration (K_{max}) to be used in the Newmark analysis; and
- Verification that the preliminary PROSHAKE-derived PHA values used in the pseudo static analyses are conservative, or to provide PHA (K_{max}) values for re-analysis.

Finally, QUAD4 was used to compare the effects of the different ground motions and to produce the input ground motion for the FLAC analyses.

Although not a formal part of selecting the seismic basis of design for the Third Runway, the design team made a careful assessment of conditions at the project site (and performance of local MSE walls) following the February 28, 2001, Nisqually earthquake (see Hart Crowser 2001c, 2001e, and 2001f). No adverse effects of that earthquake were observed in the native soils on the Third Runway fill placed prior to that time.

4.4 Liquefaction Analysis

"Liquefaction" refers to the temporary reduction in shear strength that occurs in some soils as a result of development of excess pore pressures that develop in an earthquake. Identification of the conditions that will trigger liquefaction and calculation of the post-liquefaction soil strength are important parts of the geotechnical analysis affecting stability and deformation of the Third Runway embankment and MSE walls.

Potential liquefaction is a consideration for some areas of the native soils that underlie the proposed embankment, including portions of the MSE walls. The effected soils are saturated, predominantly granular, and typically loose to medium dense. Some areas of silty or clayey soils were also found to be susceptible to liquefaction, based on screening using the "Chinese Criteria" as modified by the Corps (Kramer 1996).

Trigger Liquefaction

Determining the susceptibility of soils to loss of strength due to liquefaction is referred to as the "trigger liquefaction" analysis. Trigger liquefaction analysis is based on a recent update to the state of the art method (Youd et al. 2001). The trigger liquefaction analysis compares *in situ* soil characteristics at the Third Runway site with soil parameters that have been found to indicate liquefaction, (Seed and Harder 1990 and Idriss 1998).

The Third Runway embankment incorporates an underdrain over much of its base area, including the areas below the three MSE walls. The main purpose of the underdrain is to prevent development of any excess pore pressures within the embankment such as might develop from saturation due to infiltration or filling over existing surface seeps. Drainage provided by the underdrain and the dense compaction of the embankment fill protect the embankment itself from liquefaction. The potential occurrence of liquefaction is limited to some areas of existing native soils. The purpose of the liquefaction analysis is to identify the areas where subgrade improvement is needed to mitigate potential instability, or excessive deformation, due to liquefaction.

Details of the liquefaction analysis for the Third Runway are presented in Hart Crowser (2000k and 2001d). More recent analyses have incorporated cyclic shear stresses calculated with QUAD4.

The trigger liquefaction analysis uses a factor of safety of 1.25 to account for small increases in pore pressures that may have some effect on strength. This safety factor is separate from, and in addition to, achieving the target factor of safety in the previously discussed limit equilibrium analyses. The trigger liquefaction analysis provides the values of SPT required to trigger liquefaction which are then compared with SPT values measured at the site (Hart Crowser 2000k and 2001h). The adjustment in N-values is based on well-documented procedures (Youd et al. 2001). We also evaluated CPT data for prediction of liquefaction at the Third Runway site.

Soil conditions were evaluated for more than 25 cross sections that were selected to represent the range in subgrade and embankment/MSE wall configuration. For each cross section, the adjusted N-values required to trigger liquefaction were compared to the SPT and CPT data. Potentially liquefiable zones were delineated, and the residual strength was estimated using SPT data. The post-liquefaction stability was analyzed with limit equilibrium methods to determine the extent of subgrade improvement needed to meet the target factor of safety, as previously discussed.

Residual Strength Calculation

Large ground failures and deformations resulting from liquefaction have only been documented to occur when adjusted SPT N-values are 15 or less (Seed and Harder 1990 and Idriss 1998). However, our analysis suggested that liquefaction could potentially occur for some soil conditions at the site corresponding to N-values up to around 30. To address the potential effect of this on stability, the Third Runway design team used a soil behavior-based extrapolation of the documented residual strength of soils that have liquefied. We calculated the residual strength using corrected SPT blow counts $(N_1)_{60\text{-}cs}$ by extrapolating the residual strength curve (Idriss 1998). While there is no theoretical basis for limiting residual strength increases based on extrapolation of these curves, we limited and capped the extrapolated residual strength to 1,200 psf, corresponding to $(N_1)_{60\text{-}CS}$ = 24.

For each MSE wall or embankment cross section, the N-values which fell below the threshold value of $(N_1)_{60\text{-}CS}$ were tabulated and residual strength calculated for each soil unit. Each cross section evaluation included consideration of changes in soil parameters observed in explorations on each side of the cross section, along with the maximum groundwater level at each well (see Hart Crowser 2001j). The range of interpolation for each cross section varied, depending on how closely spaced the sections are to one another. We looked for consistent soil units that extended from one cross section to the next, as well as for local variations that distinguished one section from another.

Residual strength values were selected for liquefiable soil units. The residual strength values used for analysis were selected to provide a reasonable lower bound, looking at the range and variation of specific SPT values in each unit, where a soil unit was identified on the basis of continuous soils of similar gradation, density, and saturation. We used the lower third value of the range for residual strength in each unit if the data showed much scatter; where there was no significant scatter, we used the mean value of residual strength for the analysis.

Finally, estimated residual undrained strength values were checked to make sure they do not exceed the drained shear strength for the same type soil. The stability analyses used the lower value of either the estimated residual strength or the drained shear strength.

5.0 MSE WALLS

This section discusses why MSE walls were selected for the Third Runway, and specific design steps used for the Third Runway MSE walls.

5.1 Background

During preliminary stages of design, the Port of Seattle reviewed eight different types of retaining walls and more than 60 wall/slope combinations to identify the best means of limiting the embankment impact to Miller Creek, Walker Creek, and adjoining wetlands. The Port of Seattle selected MSE walls as the best alternative for the project based on seismic performance, constructability, historical performance, and cost-effectiveness (HNTB et al. 1999). The selection of MSE technology was confirmed via a peer review by Shannon & Wilson (1999).

After selection of MSE walls as the best alternative to limit embankment impacts to creeks and wetlands, the Port of Seattle consulted with in-house staff and experts at the University of Washington and the Washington State Department of Transportation to determine appropriate criteria for selection of an MSE wall design engineer for the Third Runway MSE walls. A formal request for qualifications was published through the mailing lists from two MSE trade associations, the Geosynthetics Materials Association and the Association for Metallically Stabilized Earth.

The Port's design team received and reviewed nine submittals from prospective designers of the Third Runway MSE walls. The Port selected RECo USA, the North American subsidiary of Terre Armee International (TAI), based on their recent experience with MSE walls of similar height and layout as those planned for the Third Runway. RECo/TAI has been responsible for design and construction of more than a dozen walls more than 90 feet in height, including two that are about the same height as the maximum wall height proposed for the Third Runway. Upon selection of RECo as the MSE wall designer, they were assimilated into the design team with HNTB and Hart Crowser. Construction of the MSE walls will be accomplished by a general contractor with components specified by the design team, and manufactured from any supplier.

5.2 Design of MSE Walls

The following steps were utilized in the progressive design and analysis of MSE walls for the Third Runway.

- An initial layout of MSE walls was developed to fit within the embankment geometry and minimize or avoid impacts to wetlands as much as possible.
- The design team met to review and discuss the design parameters, loads and details (geotechnical recommendations for design are presented in Hart Crowser 2000h). Over a period of several weeks, the design team worked through regular teleconferences to review proposed design criteria and reached consensus on the basis for design, including structural, mechanical, and aesthetic details.
- Using initially assumed reinforcement geometry, limit equilibrium analyses were used to verify that design could satisfy the AASHTO code (AASHTO 1996-2000) and other design requirements for conditions at the Third Runway site.

are subject to liquefaction. The anticipated subgrade improvements range from about 15 to 20 feet below the existing ground surface, based on information from the existing borings.

The Port reviewed nine different methods for subgrade improvement (Hart Crowser 2000g) and selected two preferred alternatives: 1) removal and replacement with compacted structural fill, or 2) stone columns. Relative feasibility, including the degree of ground improvement, constructability, quality assurance, and cost were considered for the Third Runway project., as well as potential post-construction effects on base flow to Miller Creek and adjacent wetlands (Hart Crowser 2000p).

Final selection of the removal and replacement method was made by the Port after stone column field tests were accomplished as part of the Phase 4 construction in 2001. These tests included collection of SPT and CPT data, accomplished before and after installation of more than 100 stone columns in four test patterns. The tests indicated that it would be difficult to obtain the same degree of construction quality assurance with the stone column method as with the remove and replace method. The remove and replace method was selected because it would achieve better construction reliability.

The Port has successfully monitored embankment construction to date, using the same type of soils and methods of construction that are planned for the remainder of the embankment. Construction specifications allow different types of soil materials to be used in different parts of the embankment, with appropriate moisture content limits, lift thickness, and compacted density specified to achieve a consistent quality earth fill. Compaction control and other fill quality tests are based on Federal Aviation Administration specifications (P-152) that have been modified to reflect local soil conditions.

Backfill for the subgrade improvement areas will utilize very densely compacted granular fill, compacted to 95 percent of the modified Proctor maximum density per ASTM method D 1557. The Port utilizes full-time construction inspection and services of a testing lab, field results are reviewed by both HNTB and Hart Crowser to verify conformance to the specifications.

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Table 1 - Summary of Explorations

Preliminary Evaluation & Environmental Assessment Phase

91 Borings (12 Monitoring Wells)

34 Test Pits

7 Vane Shear Tests

Final Design Phase

127 Borings (65 Monitoring Wells)

122 Test Pits

48 Cone Penetrometer Soundings

10 Vane Shear Tests

Notes:

1. Table includes explorations related to main embankment as well as for partial relocation of Miller Creek for the North Safety Area embankment construction, but does not include geotechnical studies for relocation of South 154th Street, borrow sites, or other parts of the Port of Seattle Capital Improvement Program. Hand auger explorations for wetlands delineation and shallow soil sampling not shown.

2. See Plates 1, 2, and 3 for location of explorations.

Table 2 - Laboratory Test Methods

Soil Classification	ASTM D 2488 (for visual identification only) and ASTM D 2487 (precise classification based on measured indices)
Classification of Peat	ASTM D 4427
Soil Moisture Content	ASTM D 2216
Grain Size Analysis	ASTM D 422
Atterberg Limits (Liquid Limit, Plastic Limit and Plasticity Index)	ASTM D 4318
One-dimensional Consolidation Test	ASTM D 2435
Consolidated Undrained Triaxial Test	ASTM D 4767
Unconsolidated Undrained Triaxial Test	ASTM D 2850
Direct Shear Tests	ASTM D 3080

Table 3 - Soil Parameters Used in Stability Analyses

Soil Type	Unit Weight in pcf	Drained Strength		Undrained Strength Parameters
		c' in psf	ϕ' in Degrees	S_u/σ_v'(a)
Existing Subgrade Soils				
Loose to medium dense Sand	125	0	32	-
Medium dense to dense Sand	130	0	35	-
Dense to very dense Sand	135	0	37	-
Glacial Till	130	250	40	-
Soft Peat or Organic Silt (c)	110	0	7 to 15	0.23
Medium stiff Silt/Clay (b)	115	0	30	0.23
Stiff to hard Silt/Clay (b)	115	0	30	0.23
Post Construction Soils				
Embankment Fill	135	0	35	-
Drainage Blanket	140	0	37	-
Improved Subgrade	135	0	35	-

(a) Undrained strength ratios were used for fine-grained soils based on CU triaxial results and are a function of confining pressure (σ_v'). For pseudo-static analyses, this value is assumed to reflect the combined effect of strength increase due to high rate of seismic loading and potential strength reduction due to cyclic loading.

(b) Undrained strength parameters were used for the end-of-construction cases, otherwise, drained strength properties were used.

(c) Drained friction angle for the peat was 15 degrees except at low confining pressure where a value of 7 degrees was used, see Hart Crowser (2001k).

Table 4 - Target Factors of Safety for Limit Equilibrium Analyses

Type of Analysis [1]	Target Factor of Safety Used for Third Runway MSE Wall Design	Target Factor of Safety Used by Army Corps of Engineers for Levees (EM 1110-2-1913, Corps 2000)
End of Construction	1.3	1.3
Steady State	1.5	1.4
Seismic	1.1	See note 2
Post-liquefaction	1.1	See note 2

Notes:

1. The Rapid Drawdown case used by the Corps is not applicable to the Third Runway because the Third Runway embankment does not retain water.
2. The Corps of Engineers does not specify a target factor of safety for seismic analysis. Reference to ER 1110-2-1806 (Corps 1995) indicates the Corps relies on procedures that include assessment of project hazard potential, potential earthquake motion and project features to determine design requirements for specific projects. This is essentially the same as the procedure used for the Third Runway as described in Section 4.3 and applied in the analyses described in Sections 4.1, 4.2, and 4.4.

Table 5 - Summary of Design Requirements for Third Runway MSE Walls   Sheet 1 of 2

5-1 - Static Stability Analysis [a]

	AASHTO 1996 - 2000 (Target F.S. or Other)	RECo Design Manual 1999 (Target F.S. or Other)
External Stability		
Sliding	≥1.5	≥1.5
Overturning	≥2.0	≥2.0
Eccentricity at Base	Not specifically stated	Not specifically stated
Bearing Capacity (for sliding and overturning)	≥2.0 (if justified by geotech analysis); ≥2.5 otherwise	≥2.0 (if detailed geotech info.); ≥2.5 (if general geotech info.)
Deep-Seated Stability (i.e., Global and Compound Stability)	≥1.3 (if soil param. based on lab tests); ≥1.5 otherwise	Not specifically stated
Internal Stability		
Pullout Resistance	≥1.5, where maximum friction angle of 34 deg. is used to calculate the horizontal force (if without the benefit of triaxial or direct shear testing to provide soil shear strength data)	Defaults to AASHTO, Interim 1998
Pullout Resistance[b]	$T_{max} \leq 0.55 F_y$	$T_{max} \leq 0.55 F_y$

5-2 - Seismic Stability Analysis [a]

	AASHTO 1996 - 2000 (Target F.S. or Other)	RECo Design Manual 1999 (Target F.S. or Other)
External Stability		
Sliding	≥1.1; include 100% of inertial force and 50% of dynamic thrust[c]	≥1.1
Overturning	≥1.5; include 100% of inertial force and 50% of dynamic thrust	≥1.5
Eccentricity at Base	Not specifically stated	Not specifically stated
Bearing Capacity (for sliding and overturning)	75% static (i.e., ≥1.5; include 100% inertial force and 50% of dynamic thrust [c]	Not specifically stated
Deep-Seated Stability (i.e., Global and Compound Stability)	≥1.1	Not specifically stated
Internal Stability		
Pullout Resistance	75% static; reduce F* to 80% static value; include internal inertial force[d]	Not specifically stated
Pullout Resistance	$T_{max} \leq 0.55 F_y$	$T_{max} \leq 0.55 F_y$

Table 5 - Summary of Design Requirements for Third Runway MSE Walls (cont'd) Sheet 2 of 2

5-3 - Comparison of Other Aspects of MSE Wall and Reinforced Slope Design Standards [a]

	AASHTO 1996 - 2000	**RECo Design Manual 1999**
MSE Embedment[e]	H/7 for 2H:1V slope in front of wall, where H is from top of wall at wall face to top of leveling pad	Same as AASHTO 1996
Horizontal Bench in Front of Walls Founded on Slopes	4 feet minimum width	3 feet minimum width
Calculation of Sliding for External Stability	Neglect passive resistance; include width and weight of wall facing in calculation of sliding/overturning	Not specifically stated
Leveling Pad Width	Designed to meet local bearing capacity needs and differential settlement between wall facing and backfill	Not specifically stated
Maximum particle size for reinforced backfill (see text for detailed discussion)	4 inches	6 inches
Friction Factor for Internal Reinforcement Design (backfill on ribbed steel strips)	$F^*_{max}<2.0$; $F^*_{max}<1.2 + \log C_u$, where C_u equals backfill uniformity coefficient. $C_u = 4$ for ribbed steel strips if tests are not available	Based on extensive pullout tests, but no values are specifically stated

5-4 - Comparison of Recommended Backfill Electrochemical Properties [a]

	AASHTO 1996 - 2000	**RECo Design Manual 1999**
Soil pH	5 to 10	5 to 10
Soil resistivity (at 100% saturation)	>3000 ohm-cm[f]	>3000 ohm-cm
Water soluble chloride content	<100 ppm	<100 ppm
Water soluble sulfate content	<200 ppm	<200 ppm
Organic content	1% max. (for material finer than No. 10 sieve)	Free of organics and other deleterious materials

a Note Third Runway MSE design is controlled by the "more strict" requirement when AASHTO and RECo are not the same. See also FHWA 1997 for criteria not specified by either AASHTO or RECo, such as base eccentricity (Hart Crowser 2000h).

b T equals "tension" and F_y equals "yield strength."

c Dynamic thrust determined by the pseudo-static Mononobe-Okabe analysis.

d F* is the friction factor variable, which is part of the reinforcement pullout analysis.

e MSE embedment is not a specific requirement of AASHTO or FHWA, but is provided as guidance for MSE constructed on fill.

f If soil resistivity is greater than or equal to 5,000 ohm-cm, the chlorides and sulfates requirement may be waived.

Table 6 - (from Corps 1989)

Retaining Wall Stability Criteria

Case No.	Loading Condition	Sliding Factor of Safety, FS	Shear Strength Test Required		Overturning Criteria Minimum Base Area in Compression		Minimum Bearing Capacity Safety Factor
			Soil Foundation	Rock Foundation[3]	Soil Foundation	Rock Foundation	
R1	Usual	1.5	(Q &/or S)[2,1]	Direct shear	100%[4]	75%[4]	3.0
R2	Unusual	1.33	(Q &/or S)[2,1]	Direct shear	75%[4]	50%[4]	2.0
R3	Earthquake	1.1	(Q)	Direct shear	Resultant within base	Resultant within base	>1.0

Notes

1. For soil foundations which are not free draining (permeability $< 10 \times 10^{-4}$ cm/sec), analyze for both Q and S strengths and design for the worst condition. For free-draining soil foundations (permeability $> 10 \times 10^{-4}$ cm/sec), analyze for S strengths only.

2. For construction loadings in Cases R1 and R2, use Q strengths when excess pore water pressure in the soil foundation is anticipated and S strengths when it is not anticipated.

3. The sliding analysis of a wall on rock should be based on the frictional resistance ($\tan \phi$) of concrete on rock or rock on rock. The values should be obtained from direct shear tests of pre-cut samples of concrete on rock and rock on rock, or direct shear tests of natural rock joints or bedding planes.

4. Less base area in compression than the minimum shown may be acceptable provided adequate safety against unacceptable differential settlement and bearing failure is obtained.

Project Vicinity Map

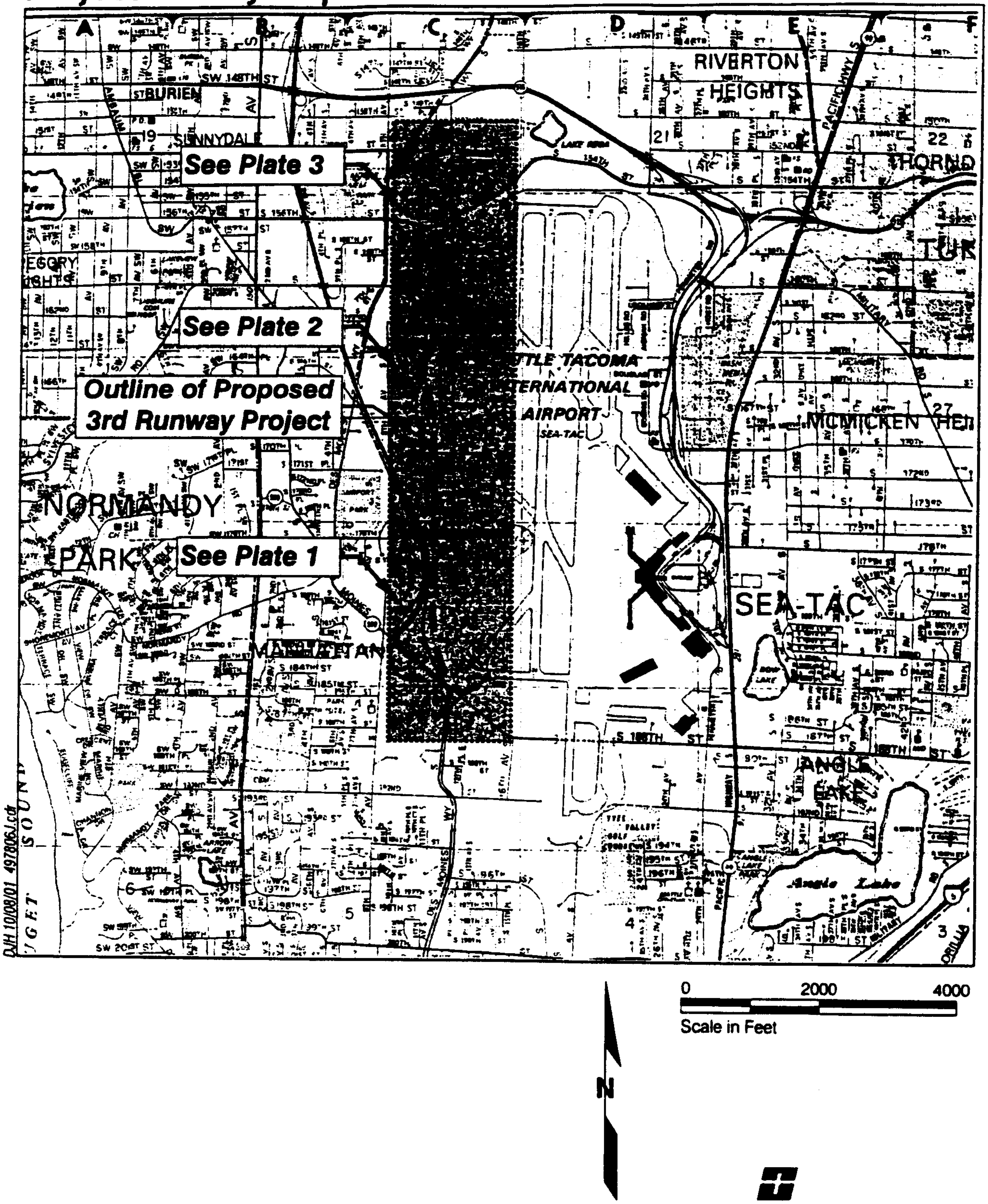

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Figure 1

Organization Chart for Third Runway Embankment Design Team and Independent Review Board

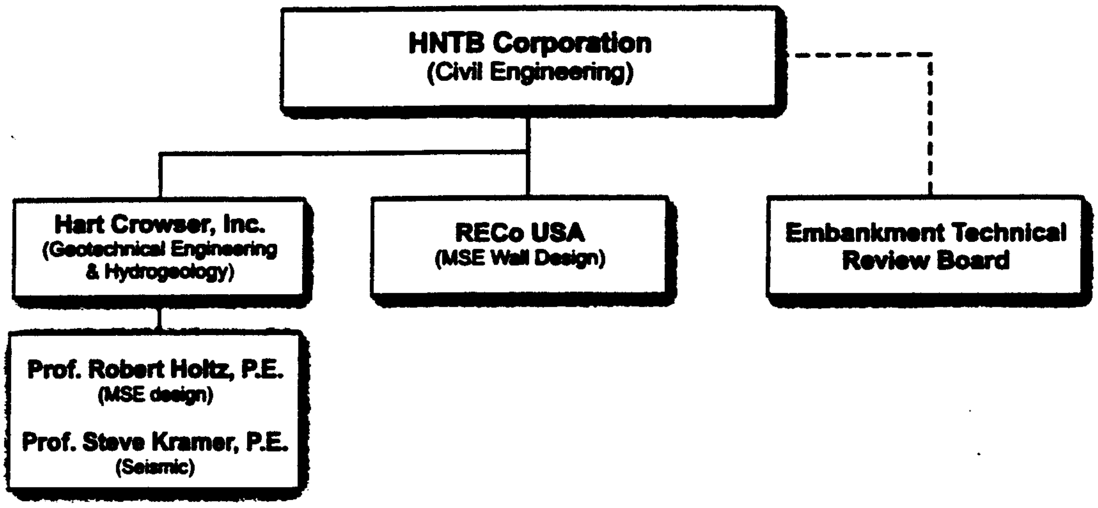

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Figure 2

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Soil Classification System and Key to Exploration Logs

Sample Description

Classification of soils in this report is based on visual field and laboratory observations which include density/consistency, moisture condition, grain size, and plasticity estimates and should not be construed to imply field nor laboratory testing unless presented herein. Visual-manual classification methods of ASTM D 2488 were used as an identification guide.

Soil descriptions consist of the following:
Density/consistency, moisture, color, minor constituents, MAJOR CONSTITUENT, additional remarks.

Density/Consistency

Soil density/consistency in borings is related primarily to the Standard Penetration Resistance.
Soil density/consistency in test pits is estimated based on visual observation and is presented parenthetically on the test pit logs.

SAND or GRAVEL Density	Standard Penetration Resistance (N) in Blows/Foot	SILT or CLAY Consistency	Standard Penetration Resistance (N) in Blows/Foot	Approximate Shear Strength in TSF
Very loose	0 - 4	Very soft	0 - 2	<0.125
Loose	4 - 10	Soft	2 - 4	0.125 - 0.25
Medium dense	10 - 30	Medium stiff	4 - 8	0.25 - 0.5
Dense	30 - 50	Stiff	8 - 15	0.5 - 1.0
Very dense	>50	Very stiff	15 - 30	1.0 - 2.0
		Hard	>30	>2.0

Moisture

Dry	Little perceptible moisture
Damp	Some perceptible moisture, probably below optimum
Moist	Probably near optimum moisture content
Wet	Much perceptible moisture, probably above optimum

Minor Constituents

	Estimated Percentage
Not identified in description	0 - 5
Slightly (clayey, silty, etc.)	5 - 12
Clayey, silty, sandy, gravelly	12 - 30
Very (clayey, silty, etc.)	30 - 50

Legends

Sampling Test Symbols

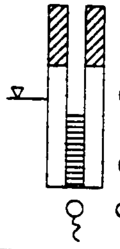
BORING SAMPLES

☒	Split Spoon
⧅	Shelby Tube
▥	Cuttings
◫	Core Run
*	No Sample Recovery
P	Tube Pushed, Not Driven

TEST PIT SAMPLES

☒	Grab (Jar)
⧄	Bag
⧅	Shelby Tube

Groundwater Observations



Surface Seal

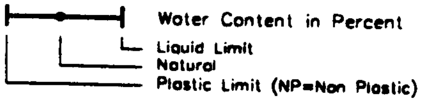
Groundwater Level on Date (ATD) At Time of Drilling

Observation Well Tip or Slotted Section

Groundwater Seepage (Test Pits)

Test Symbols

GS	Grain Size Classification
CN	Consolidation
UU	Unconsolidated Undrained Triaxial
CU	Consolidated Undrained Triaxial
CD	Consolidated Drained Triaxial
QU	Unconfined Compression
DS	Direct Shear
K	Permeability
PP	Pocket Penetrometer Approximate Compressive Strength in TSF
TV	Torvane Approximate Shear Strength in TSF
CBR	California Bearing Ratio
MD	Moisture Density Relationship
AL	Atterberg Limits



PID	Photoionization Detector Reading
CA	Chemical Analysis
DT	In Situ Density Test

DJH 1=1 497806 A-1 Boring key.DWG

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Soil Plasticity Summary Plot

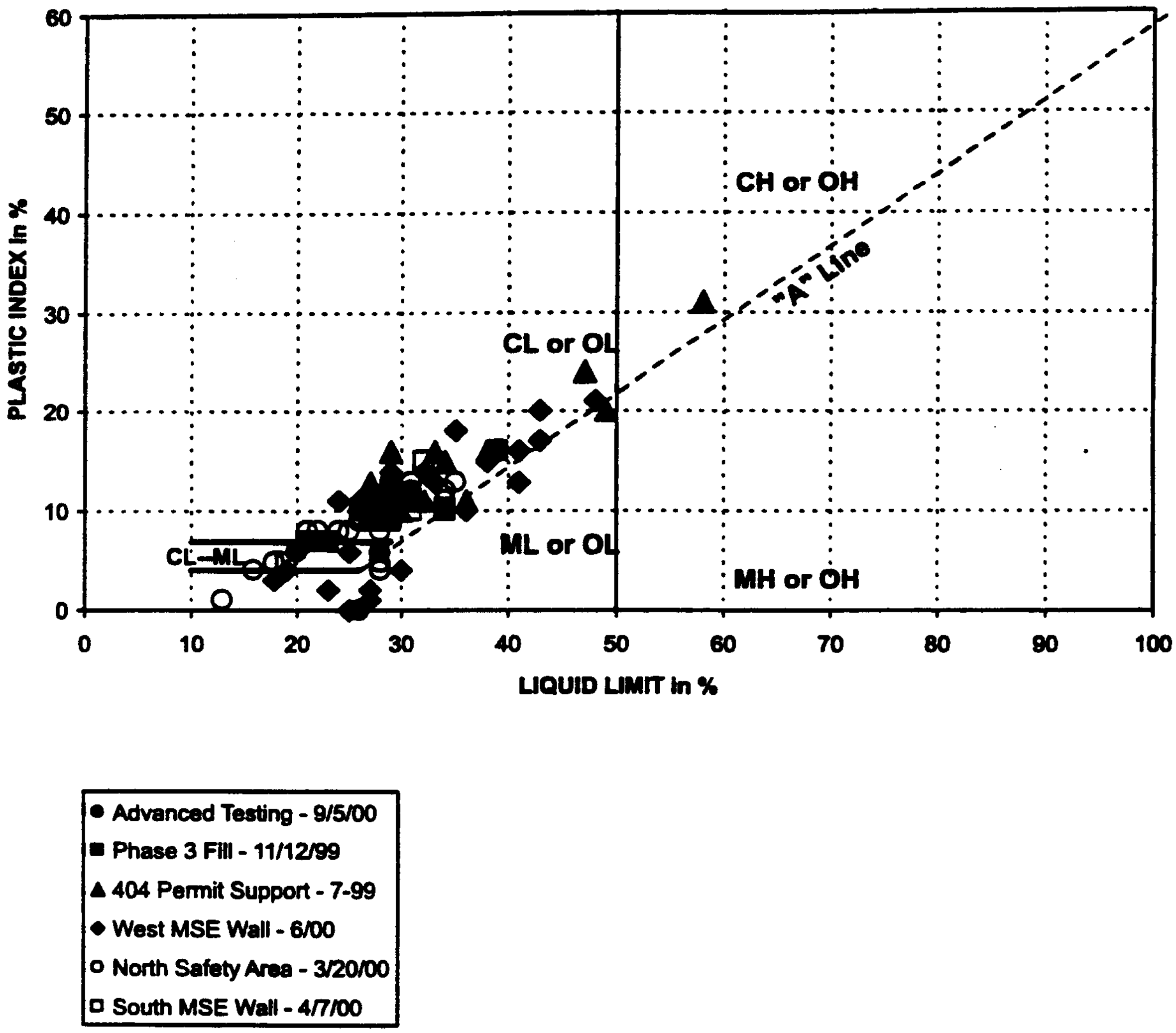

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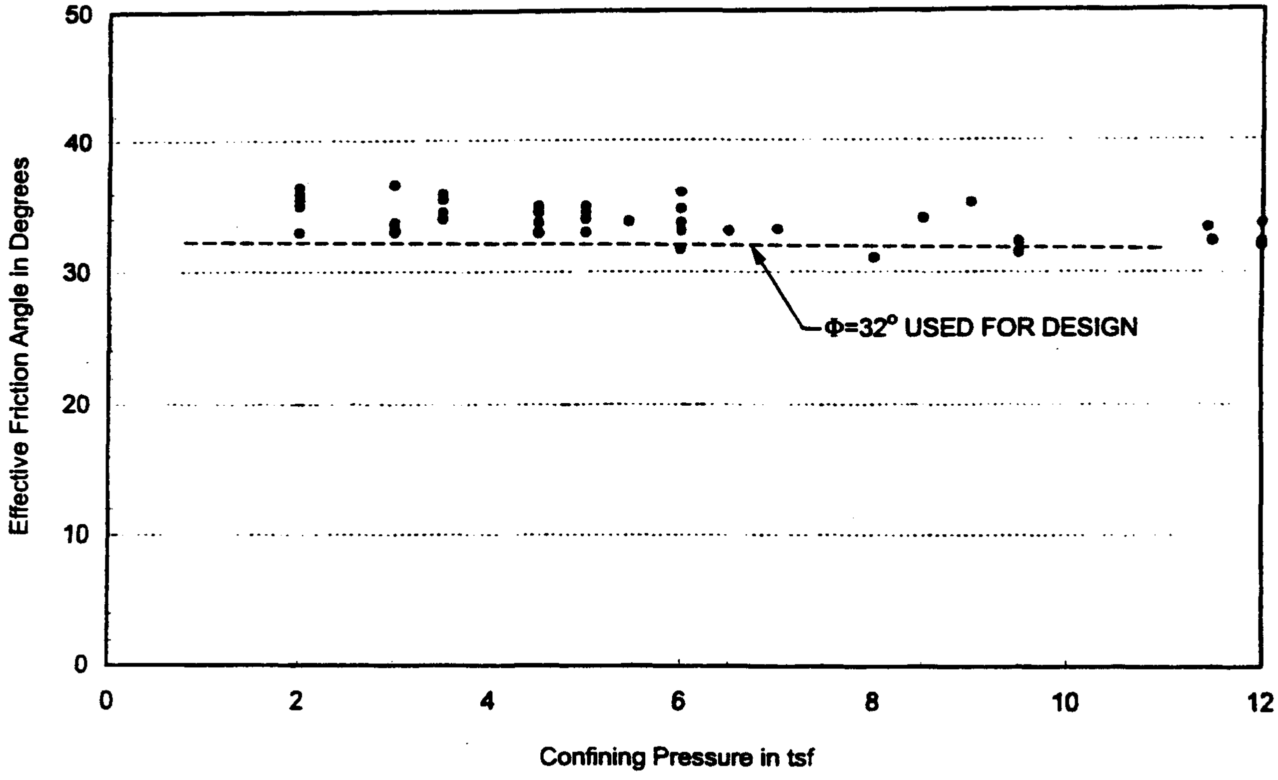
Figure 4

Effective Friction Angle vs. Confining Pressure for Clays and Silts



● Soil Sample Test Result

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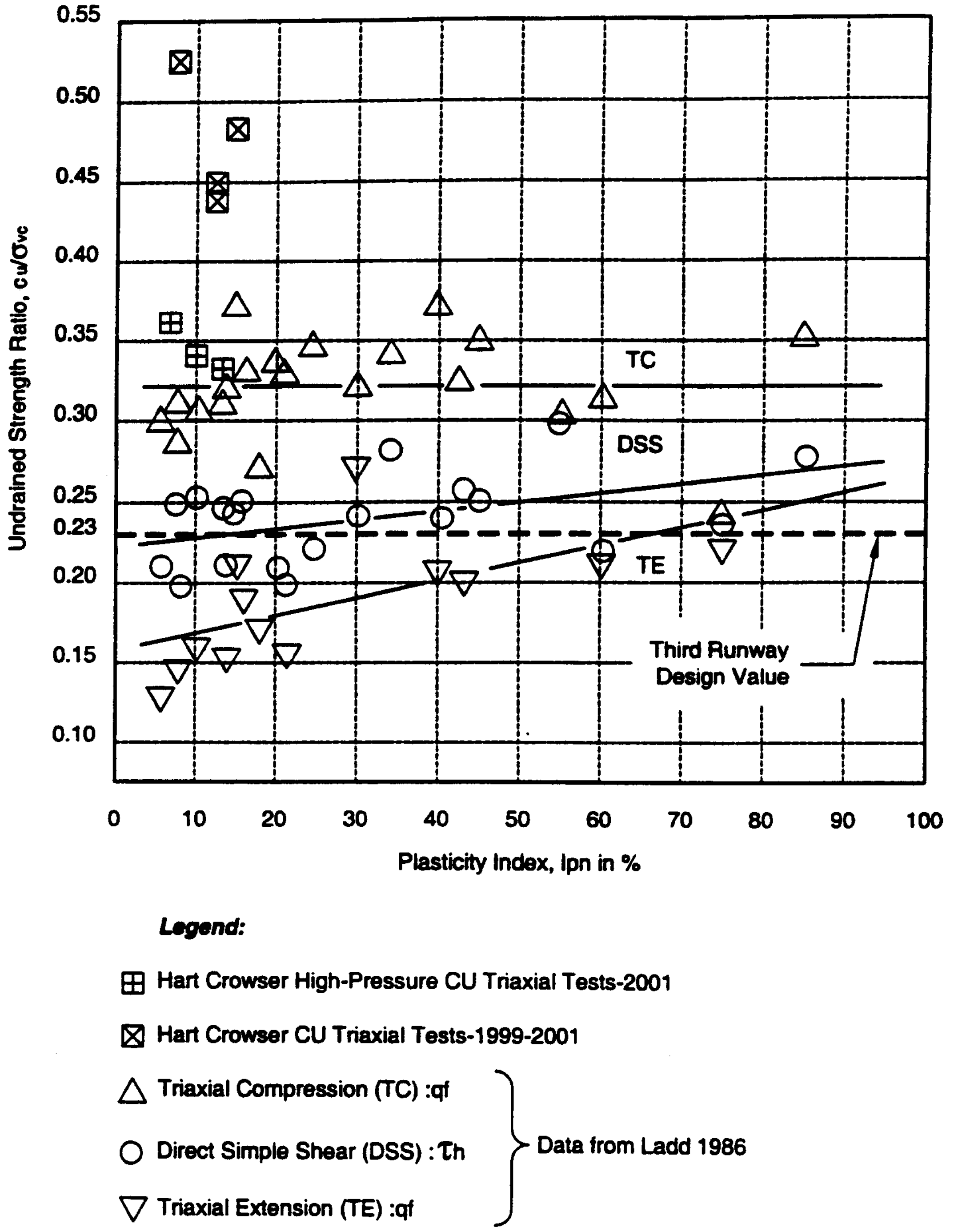
Figure 5

Undrained Strength Ratio for Normally Consolidated Clays and Silts Compared to Design Value and Published Data



49786098.DWG CAS NOT TO SCALE

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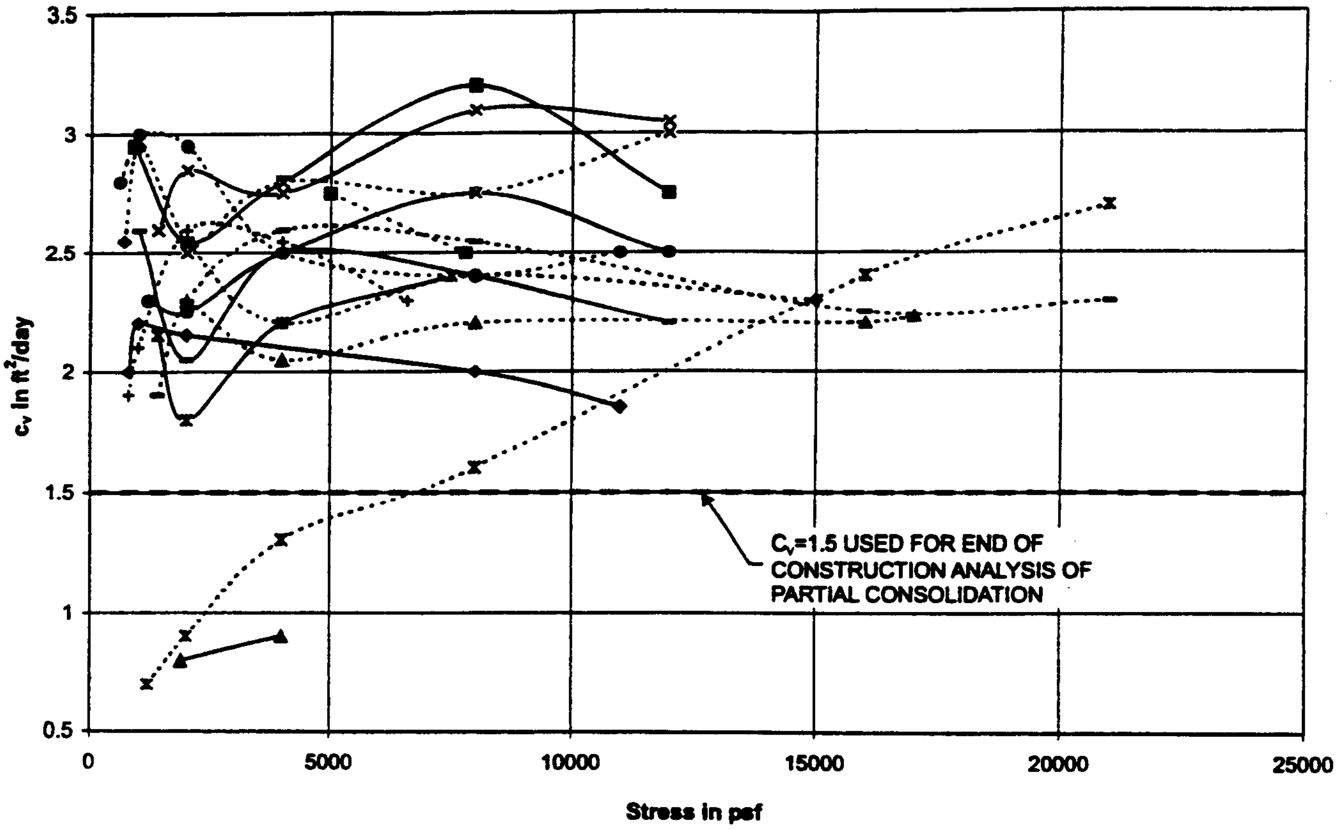
Figure 6

Coefficient of Consolidation vs. Embankment Load Range



Note:
The lower and upper stresses for each sample represent *in situ* and *in situ* + embankment load respectively, such that the results are applicable for the stress range during construction.

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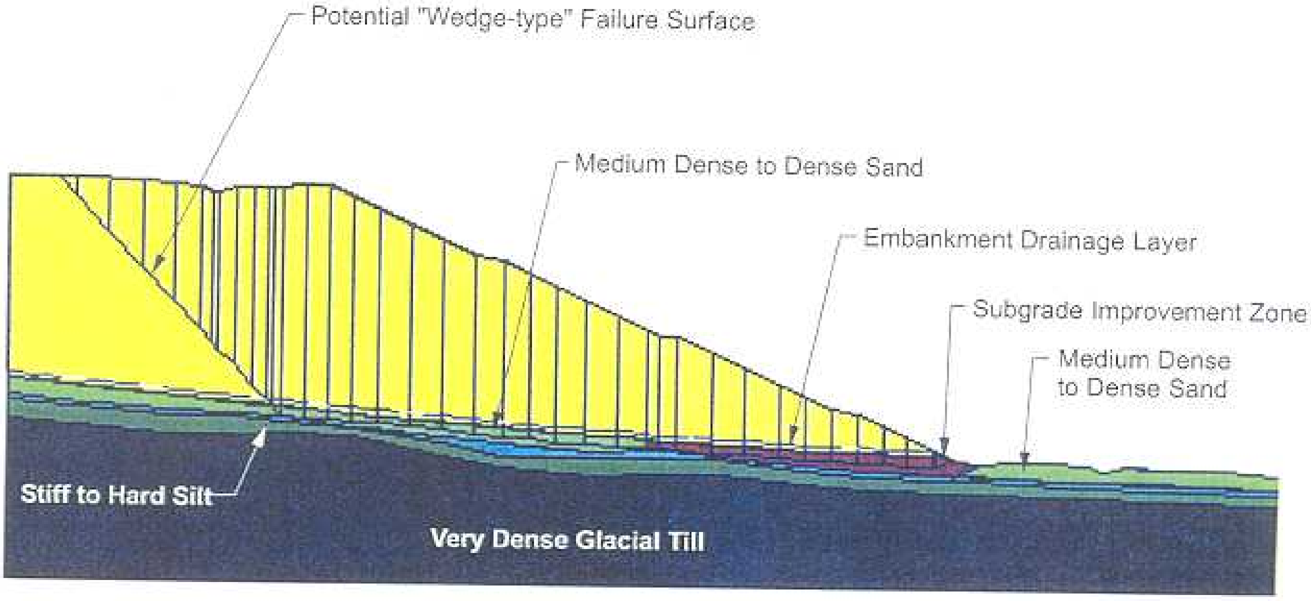
Figure 7

Equilibrium Stability Analysis for a 2H:1V Embankment Section



Note:
This figure illustrates a typical limit equilibrium analysis using Spencer's method with the program SLOPE/W. Each stability analysis includes calculating factor of safety for dozens of such surfaces. The limits (width and depth) of the subgrade improvement zone are adjusted so the analysis proceeds until all potential failure surfaces meet the target factor of safety. Subgrade improvements are constructed to mitigate weak or compressible soil or to assure stability.

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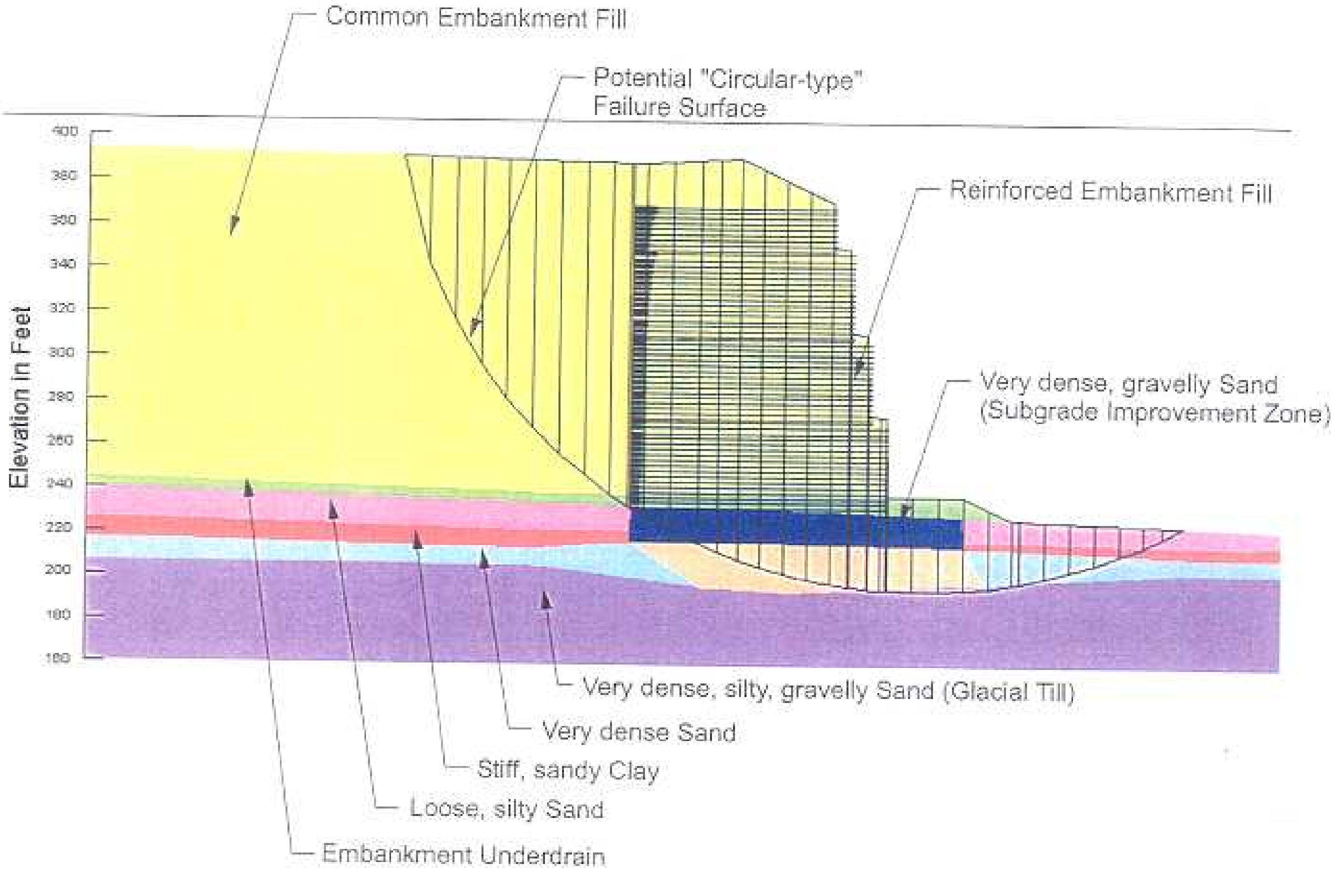
Figure 8

Global Stability Analysis for a West MSE Wall Section



Note:
Global stability analysis is a type of limit equilibrium analysis that looks for potential failure surfaces that extend below and outside the MSE reinforcing.

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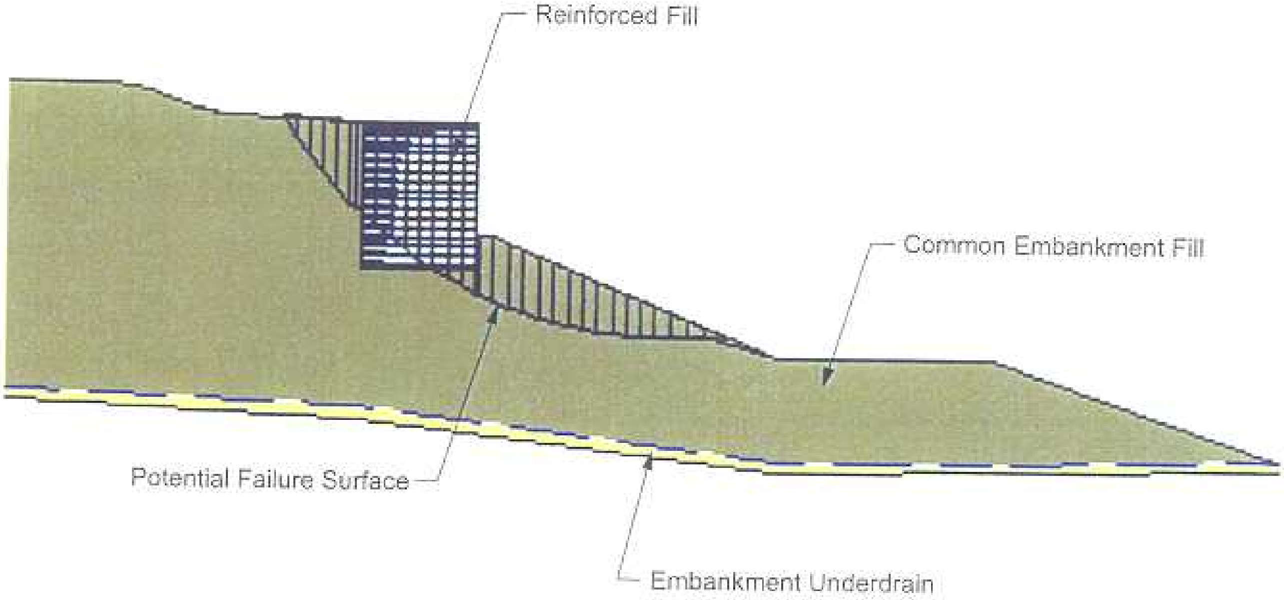
Figure 9

Compound Stability Analysis for a South MSE Wall Section



Note:
Compound stability analysis is a type of limit equilibrium analysis that looks for potential failure surfaces that extend through the soil reinforcing. As needed, the length, thickness, and/or depth of embedment of the MSE reinforcing can be adjusted for iterative analyses until all potential failure surfaces meet target factors of safety.

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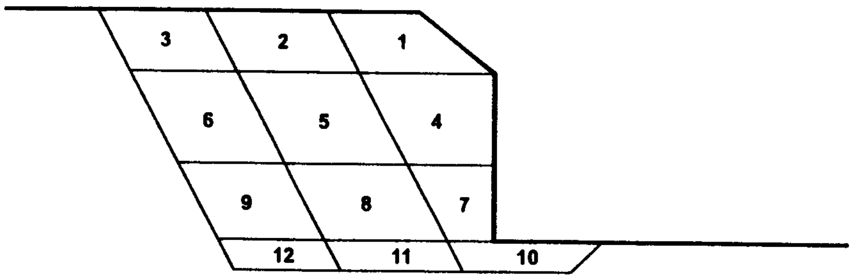
Figure 10

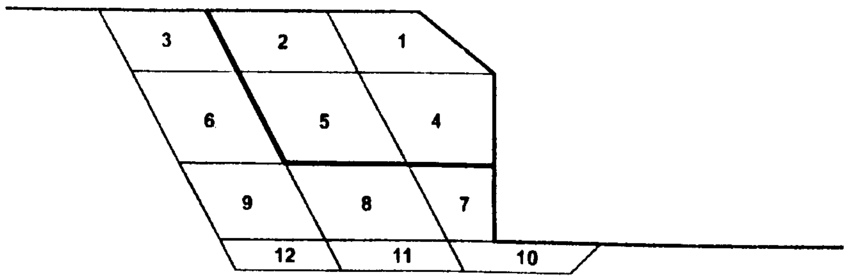
Illustration of Newmark Deformation Analysis



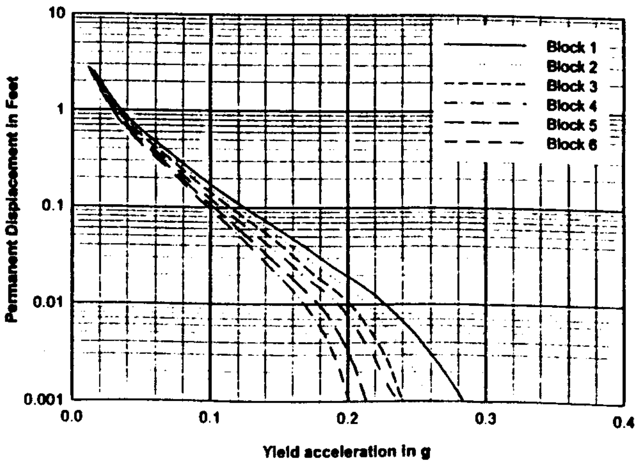
Note:
Illustration of numbering system used for identifying wedges. (For clarity, soil and wall details not shown)

Block ID	k_y	k_{max}
1	0.43	0.45
2	0.59	0.44
3	0.64	0.42
4	0.56	0.36
5	0.53	0.34
6	0.61	0.33
7	0.61	0.33
8	0.48	0.28
9	0.53	0.27
10	0.52	0.28
11	0.10	0.24
12	0.44	0.24

Note:
Seismic shaking produces displacement of a wedge when k_{max} exceeds k_y.



Note:
Illustration of potential failure surface for Wedge 5 includes volume of potential failure wedges 1, 2, and 4.



Note:
Permanent displacement varies depending on yield acceleration and k_{max} for each potential failure wedge.

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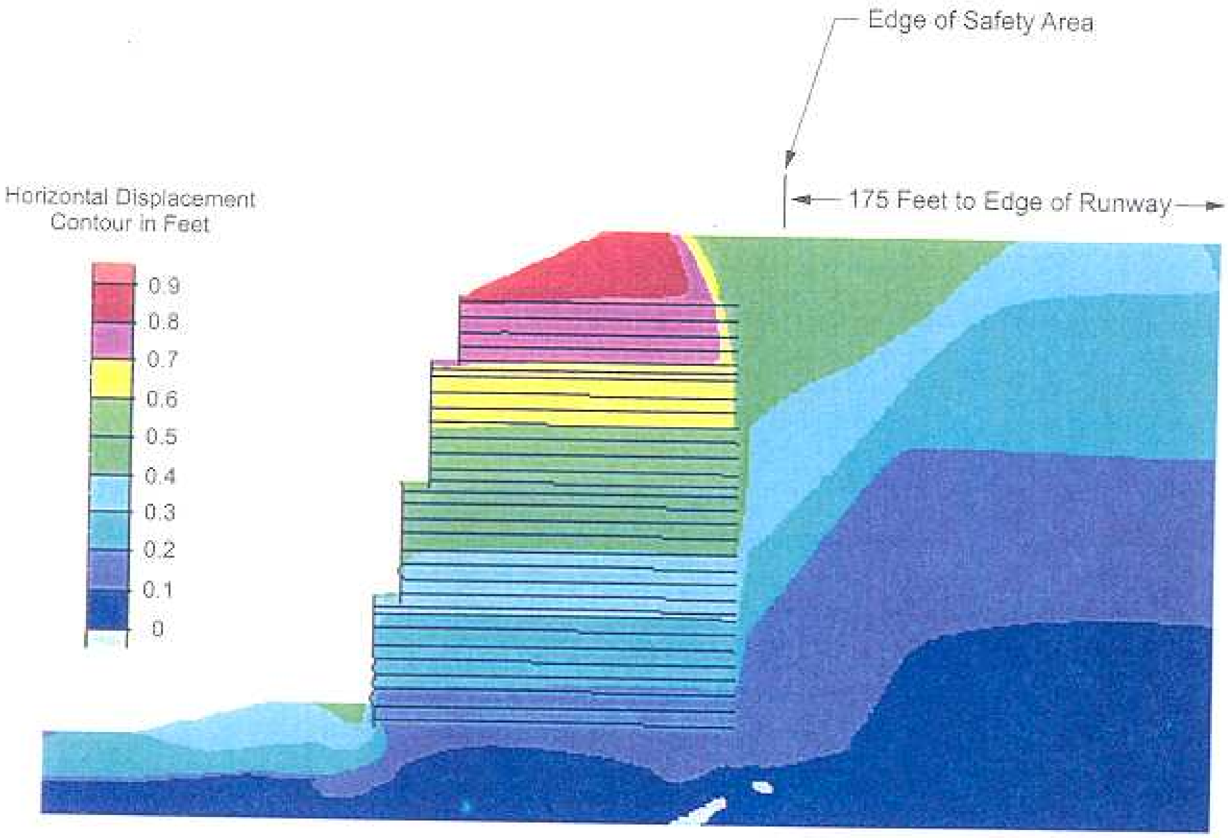
Figure 11

FLAC Model Deformation Analysis for a West MSE Wall Section



Note:
Illustration of horizontal ground displacement from FLAC model after design level earthquake shaking. Colors indicate approximate zones of uniform displacement. Details of soil horizons and subgrade improvement omitted from this figure for clarity.

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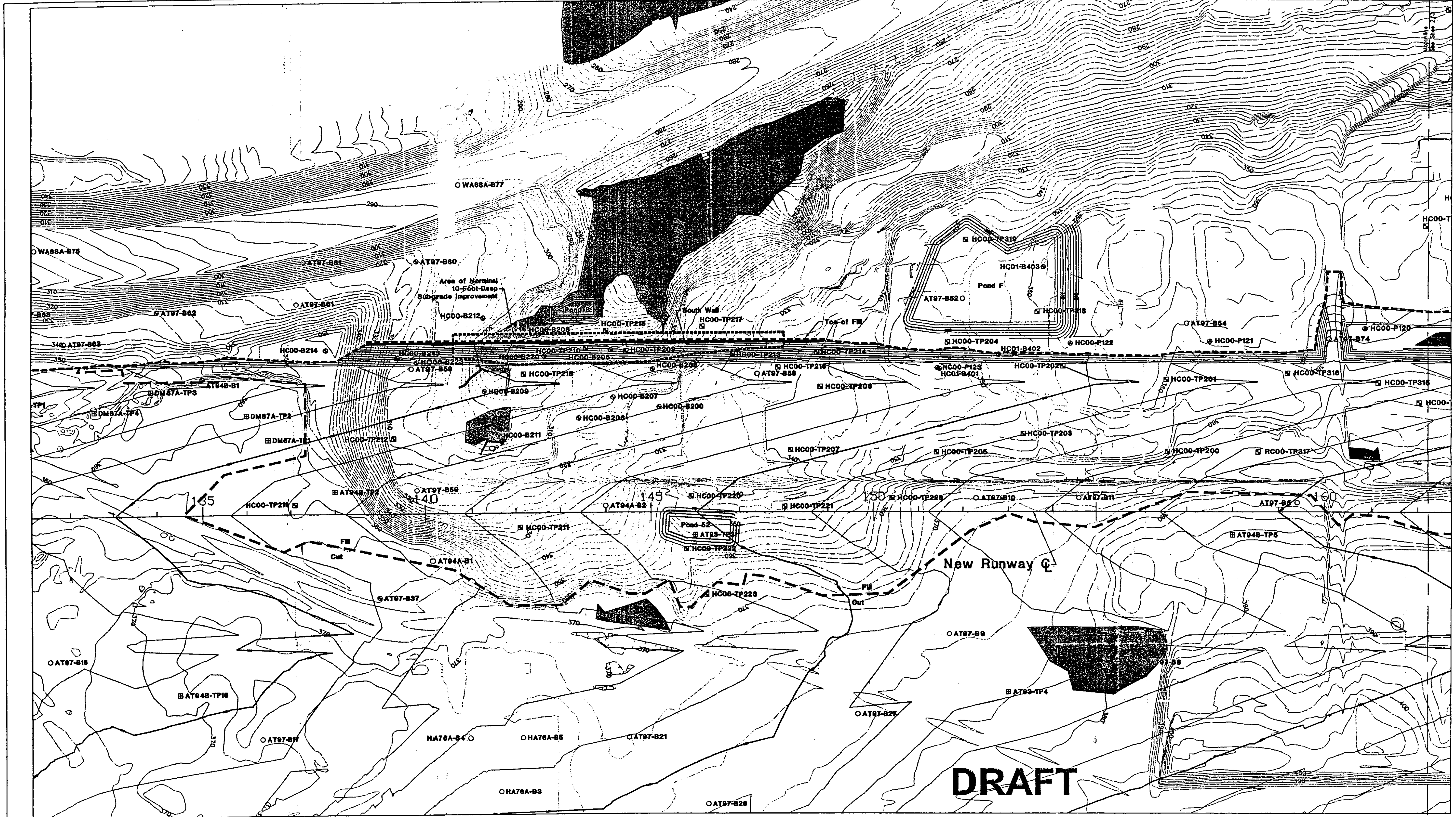
Figure 12



Notes:
1) Base map prepared from drawings provided by HNTB entitled "X_TOPO.dwg", dated February 15, 2001 and "P_final.dwg", dated June 5, 2001. Wetlands delineations prepared from drawing provided by Parametrix entitled, "w_022201.dwg", dated February 22, 2001.
2) Limits of subgrade improvement are tentative pending completion of final design analyses.

Exploration Location and Number

⊞	⊠ HC00-TP212	Test Pit
○	⊙ RT97-B17	Boring
	⊕ HC00-P123	Cone Penetrometer
▬		Wetland

— — 340 — —	Pre–Construction Elevation Contours in Feet
—— ▬ ——	Post–Construction Elevation Contours in Feet
▪▪▪▪▪▪▪▪	Proposed Limits of Subgrade Improvement
▬ ▬ ▬ ▬	Edge of Embankment Fill

N

0 100 200

Scale in Feet

RC 11/1/01 1=100 (xref)see drawing file/4978–X.pc2 497806097

Bench Mark:

Proj. Mgr.:	M. J. BAILEY	Designed By:	M. J. BAILEY	Drawn By:	R. CHAO
Checked By:	GTB	Approved By:	MJB	Date:	10/30/01

No.	Date	By	Revision

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Seattle, Washington 98102–3699
FAX 206.328.5581
206.324.9530

SEA-TAC THIRD RUNWAY

SITE AND EXPLORATION PLAN
SOUTH WALL AREA

Drawing Size:	Scale:	Date Issued:	Drawing Type:	Job No.:	SHEET:	PLATE:
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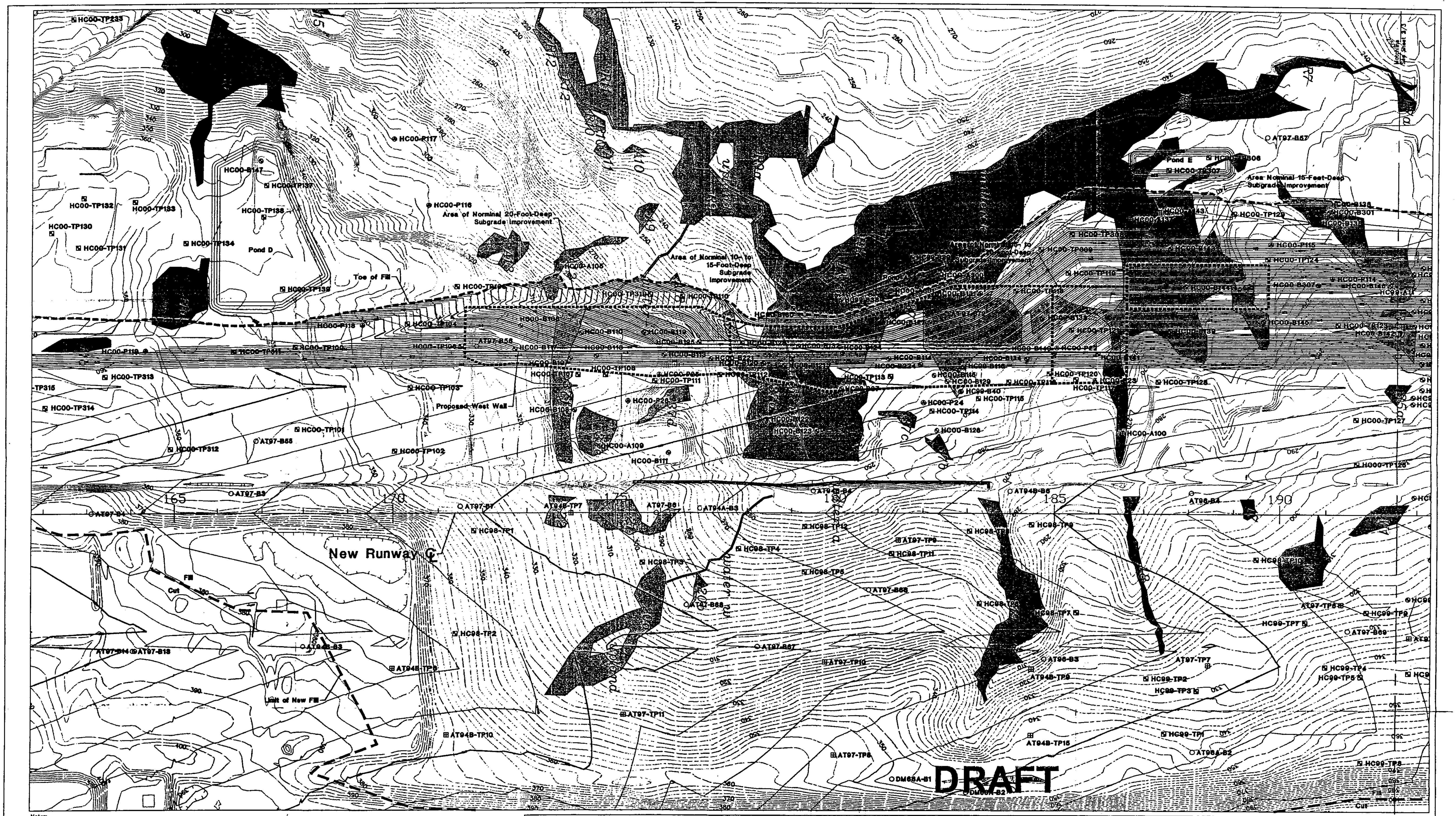

Notes:
1) Base map prepared from drawings provided by HNTB entitled "X_TOPO.dwg", dated February 15, 2001 and "P_final.dwg", dated June 5, 2001. Wetlands delineations prepared from drawing provided by Parametrix entitled, "w_022201.dwg", dated February 22, 2001.
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Exploration Location and Number

⊞	⊠ HC00-TP212	Test Pit
○	⊖RT97-B17	Boring
	⊕HC00-P123	Cone Penetrometer
	●	Wetland

---340--- Pre-Construction Elevation Contours in Feet

——— Post-Construction Elevation Contours in Feet

▪▪▪▪▪▪ Proposed Limits of Subgrade Improvement

— — — Edge of Embankment Fill

N

0 100 200

Scale in Feet

RC 11/1/01 1=100 497806096 (xref)see drawing file/4978-x.pc2

Bench Mark:					
Proj. Mgr.: M. J. BAILEY		Designed By: M. J. BAILEY		Drawn By:	R. CHAO
Checked By: GTB		Approved By:	MJB	Date:	10/30/01
No.	Date	By	Revision		

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SEA-TAC THIRD RUNWAY

SITE AND EXPLORATION PLAN
WEST WALL AREA

Drawing Size:	Scale:	Date Issued:	Drawing Type:	Job No.:	SHEET:	PLATE:
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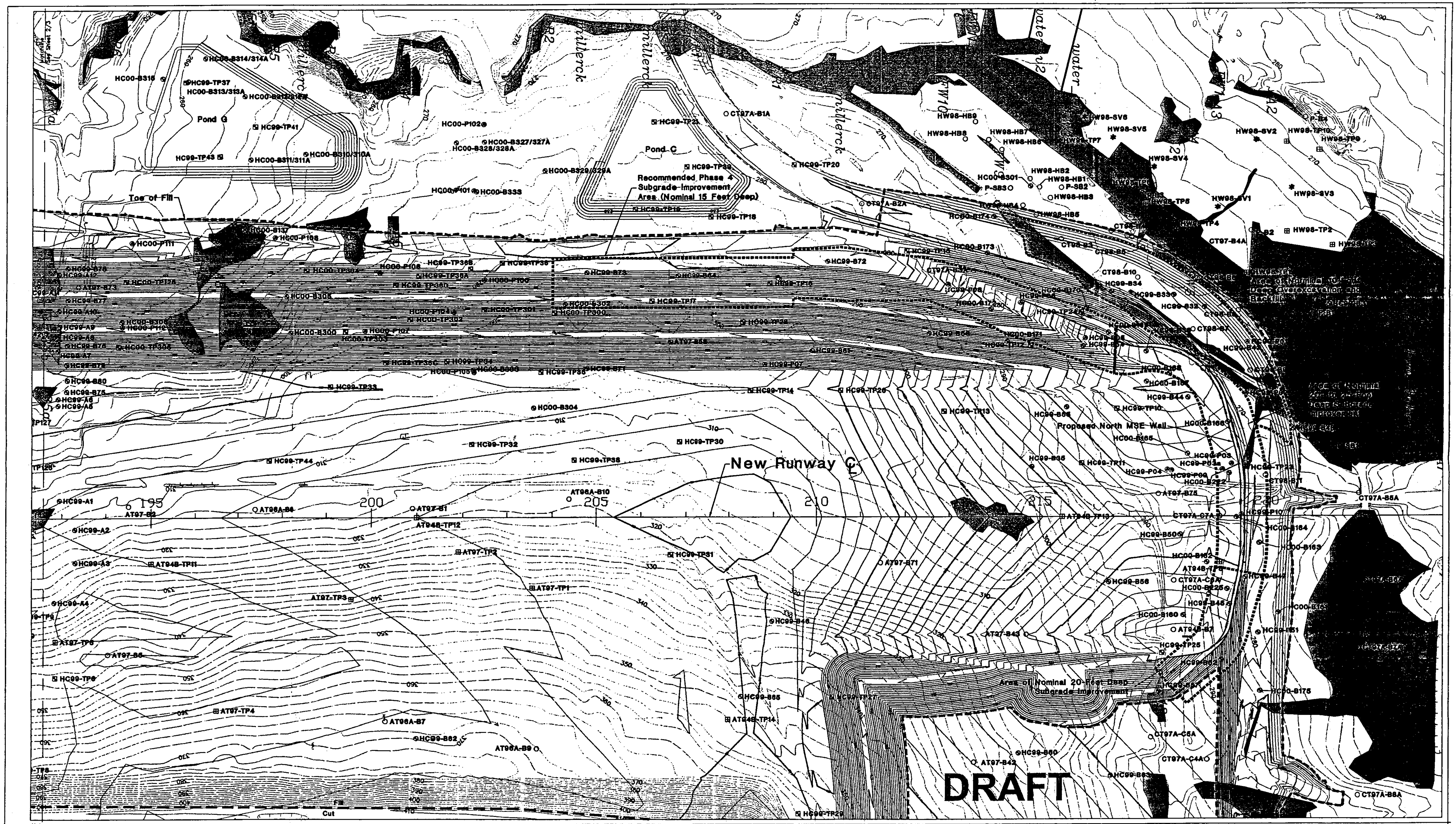

Notes:

1) Base map prepared from drawings provided by HNTB entitled "X_TOPO.dwg", dated February 15, 2001 and "P_final.dwg", dated June 5, 2001. Wetlands delineations prepared from drawing provided by Parametrix entitled, "w_022201.dwg", dated February 22, 2001.

2) Limits of subgrade improvement are tentative pending completion of final design analyses.

Exploration Location and Number

⊞	⊠ HC00-TP212	Test Pit
○	⊖ RT97-B17	Boring
	⊕ HC00-P123	Cone Penetrometer
	●	Wetland

— — — 340 — — —	Pre-Construction Elevation Contours in Feet
——— 350 ———	Post-Construction Elevation Contours in Feet
■■■■■■■■	Proposed Limits of Subgrade Improvement
▬ ▬ ▬ ▬	Edge of Embankment Fill

N

0 100 200

Scale in Feet

RC 11/1/01 1=100 (xref)see drawing file/4978-X.pc2 497806095.dwg

Bench Mark:

Proj. Mgr.: M. J. BAILEY	Designed By: M. J. BAILEY	Drawn By: R. CHAO
Checked By: GTB	Approved By: MJB	Date: 10/30/01

No.	Date	By	Revision

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206.324.9530

SEA-TAC THIRD RUNWAY

SITE AND EXPLORATION PLAN
NORTH SAFETY AREA

Drawing Size:	Scale:	Date Issued:	Drawing Type:	Job No.:	SHEET:	PLATE:
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