MASW to Investigate Subsidence
in the Tampa, Florida Area

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Final Report to

ELM Consulting LLC
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Open-file Report No. 99-33

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Summary

The shear wave velocity field, calculated using the Multi-channel Analysis of Surface Waves (MASW) method (Park et al., 1999; Xia et al., 1999), helped identify variability in the lateral continuity of near-surface layers in and around surface structures with damage that appears to be related to non-uniform earth settling in the Tampa, Florida area (Figure 1). Depths of investigation extended from a few feet below ground surface (BGS) to as much as 100 ft BGS in some cases. Anomalies interpreted in “bedrock” near all six structures studied could be related to subsidence effects observed at the ground surface. Previous drilling and resistivity investigations at these six sites has not conclusively identified a geologic/structural situation that could be definitively correlated to sinkhole activity. When comparing this study to previous investigations using this surface wave imaging technology at sites around the country (Miller and Xia, 1999a; Miller and Xía, 1999b), it is interesting to note the inability to detect or discern a unique velocity pattern consistent with all subsidence features. In most cases, an anomalously low velocity within bedrock was detected and proposed to be indicative of dissolution and the subsidence implied by change in the shallow low velocity zone. Extrapolations between the “bedrock” features and the affected area on or near the ground surface required speculation as to the connectivity of the features interpreted to be subsidence related within the “unconsolidated” sediments. In each of the six areas studied, subsurface variations in shear wave velocity patterns above the interpreted/inferred bedrock surface were interpreted that could be associated with the subsidence responsible for structural damage.

Calculating the shear wave velocity field from surface wave arrivals can generally be accomplished with a high degree of accuracy regardless of cultural noise or obstacles. Data for this study were acquired in and around occupied personal residences requiring adaptations be made for cement and asphalt as well as for limitations and restrictions in generating acoustic energy inside houses, around swimming pools, and through gardens. Care was taken to insure no data carried artifacts related to surface features and all data were acquired with special attention placed on the spread location relative to surface materials and structures. Comparisons of data characteristics recorded from geophones with steel baseplates to those with spikes revealed no significant difference in wavetrain properties or calculated dispersion curves. Of particular
Figure 1. Map showing relative placement of sites near Tampa, Florida.
concern during data acquisition was geophone placement inside houses where floor coverings ranged from carpet to ceramic tile to cement. Unlike recording concerns prominent when using other types of acoustic waves, surface waves seem to have only limited dependence on changes in receiver coupling. Non-source noise recorded on surface wave data reduces the quality of the dispersion curve but does not usually prevent an accurate and robust inversion.

MASW provides shear wave velocity profiles accurately (15%) representing average shear wave velocities for a particular subsurface volume (Xia et al., in review). Velocities measured during this study ranged from just over 100 ft/sec to around 2100 ft/sec. Localized changes of over 1300 ft/sec (400%) across distances less than 10 ft were common around areas with observed structural damage. Velocity inversions are prominent within the upper 20 ft and likely relate to stiffer clays or partially cemented sediments in close proximity to sand or gravel zones. The sensitivity of shear wave velocities to changes in sediment makeup correlates to differing degrees with other imaging techniques and/or observed differences in material composition. There does not seem to be a unique characteristic or property of the shear wave velocity field diagnostic of subsidence activity at all the Tampa sites studied. Interpreting these data requires incorporation of drilling, borehole measurements, and other geophysical soundings. Data acquired for this study, in general, have relative gradational vertical and horizontal variations in shear wave velocity when compared to data from other sites with noted subsidence activities. This apparent lack of sensitivity could be unique to the structural properties of the sediments in this area (subsidence results in only subtle changes in stiffness/rigidity), resolution limitations of the method, or the subsidence mechanics in the Tampa, Florida area. Sediments described in drill cuttings and correlated to blow counts seem to be generally consistent with velocity profiles and associated gradients.

Interpreting changes in lithology with this technique has routinely involved correlating high velocity gradients and measured velocities to ground truth. Velocity fields at most of the six Tampa sites possess distinguishable velocity inversions at or around 10 ft to 20 ft BGS with large velocity gradients immediately above and below. High velocity closures, likely indicative of extreme lateral variability in sediment cementation, appear sporadically within the unconsolidated portion of the section. These localized changes in cementation will strongly influence the linearity and preferred subsidence migration path from the bedrock to ground surface. Interpreting the bedrock surface based solely on the high velocity gradient could not be done with
confidence using only the shear wave data. The gradational nature of the shear wave velocity field makes interpreting the surface of bedrock a bit speculative across most of the lines. However, incorporating drill information with interpretations of laterally continuous high velocity gradients makes it possible to trace the top of bedrock beneath most sites. The roughness of the bedrock surface strongly influences the gradational nature of the velocity field in proximity to bedrock. This roughness is suggestive of dissolution or erosional activity.

Large velocity gradients in the shear wave velocity field near the expected depth of bedrock (stiffer layers seeming more laterally continuous) were used as diagnostic of the bedrock surface, while localized lateral decreases in the shear wave velocity below the bedrock surface were considered characteristic of fracture zones or dissolution features. The depth-to-bedrock interpreted using shear wave velocity data and drilling logs possesses significantly higher resolution than drilling alone. Advantages of mapping variations in the shallow stratigraphy with the shear wave velocity field calculated from surface waves using MASW include a disregard for velocity inversions, ease of generating and propagating surface wave energy in comparison to body wave energy, being oblivious to cultural noise (mechanical or electrical), and sensitivity to lateral changes in velocity.

Introduction

Surface waves traditionally have been viewed as noise on multichannel seismic data designed to image environmental, engineering, and groundwater targets (Steeples and Miller, 1990). A recent development incorporating concepts from spectral analysis of surface waves (SASW) developed for civil engineering applications (Nazarian et al., 1983) with multi-trace seismic acquisition methods commonly used for petroleum applications (Glover, 1959) shows great potential for detecting, and in some cases delineating, anomalous subsurface materials. Extending the common use of surface wave analysis techniques from estimating 1-D shear wave velocities to detection and/or imaging required a multichannel approach to data acquisition and processing. Integrating the MASW method with CMP-style data acquisition permits the generation of a laterally continuous 2-D shear wave velocity field cross-section (Park et al., 1996; Xia et al., 1997; Xia et al., 1998; Park et al., 1999; Xia, et al., 1999). The MASW method as used here requires minimal processing and is relatively insensitive to cultural interference. Mating MASW with the redundant sampling approach used in CMP data acquisition provides a non-
invasive method of delineating horizontal and vertical variations in near-surface material properties.

Continuous acquisition of multichannel surface wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels (Park et al., 1998), mapping the bedrock surface (Xia et al., 1998; Miller and Xia, 1999a), locating remnants of underground mines (Park et al., 1999), and delineating fracture systems (Park et al., 1997; Miller and Xia, 1999b). Extending this technology from sporadic sampling to continuous imaging required the incorporation of MASW with concepts from the CDP method (Mayne, 1962). Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross-section of the shear wave velocity field. Cross-sections generated in this fashion contain specific information about the horizontal and vertical continuity and physical properties of materials as shallow as a few inches to over 300 ft BGS in some settings.

Subsidence-prone areas are likely targets for this type of imaging. Decreases in the shear wave velocity related to decreases in compaction or localized increases in shear wave velocity associated with the tension dome surrounding subsurface cavities are key indicators of either subsidence activity or areas with a strong potential for roof collapse. In situations where gradual subsidence is or has been active, a dramatic drop in shear wave velocity will be characteristic of earth materials that have begun to collapse into voids formed at depth. This low velocity zone generally produces a characteristic signature in the shear wave velocity field. Since the shear wave velocity of earth materials changes when the strain on those materials becomes “large,” it is reasonable to suggest load-bearing roof rock above mines or dissolution voids may experience elevated shear wave velocities due to loading between pillars, or, in the case of voids, loading between supporting side walls. Key to exploiting surface waves as a site characterization tool is their sensitivity to shear wave velocity, compressional wave velocity, density, and layering in the half space.

Several key characteristics of surface waves and surface wave imaging make application of this technique possible in areas and at sites where other geophysical tools have failed or provided inadequate results. First and probably foremost is the ease with which surface waves can be generated. The relative high amplitude nature of surface waves (in comparison to body waves) makes possible their application in areas with elevated levels of mechanic/acoustic noise. A layer over half space is all that is necessary to propagate surface waves. It is one of the few
acoustic methods that does not require velocity to increase with depth and/or a contrast (i.e., velocity, density, or combination [acoustic impedance]). Conductivity of soils, electrical noise, conductive structures, and buried utilities all represent significant problems or at least important considerations for electrical or EM methods. These have little or no impact on the generation or propagation and generally have no influence on the processing or interpretation of surface wave data. This flexibility in acquisition and insensitivity to environmental noise allows successful use of shear wave velocity profiling in areas where other geophysical methods might be limited.

This study was focused in and around structures with documented, visible physical damage that appears to be the result of non-uniform foundation settling. Characterizing the near-surface materials supporting these structures is critical to determining the mechanism responsible for the physical damage. Materials present above “bedrock” are classified by most borehole lithologic descriptions as combinations of silts, sands, and clay in differing concentrations and cementation. Most boreholes in and around the areas investigated reach refusal in stiff clays or silts. Based on correlation with shear wave velocity profiles it is very likely the silt or stiff clay is at or very near the top of bedrock (likely limestone). It is the intent of these data to provide a sampling of the shear wave velocity field (directly related to stiffness), permitting anomalous zones possibly indicative of subsidence activity to be detected and drill investigated. Lines were deployed after considering optimum sampling of subsiding materials, maximum line lengths, and line-to-line correlations. For ten of the twelve profiles, acquisition parameters were designed to image materials between about 10 ft to 100 ft. The remaining two profiles focused on the 5 to 50 ft BGS depth range. The primary objective of this study was to improve the overall understanding of the subsidence mechanism at each of these uniquely different sites with sufficient resolution to allow drill confirmation.

Data Acquisition

Data were acquired along intersecting orthogonal lines when possible, and when not, lines were placed to optimize subsurface sampling and access to suspect areas. Standard CMP roll-along techniques were used to record nominal 48-channel shot records along each line. Asphalt and concrete surfaces necessitated the outfitting of geophones with metal baseplates. Geophones planted in grassy areas employed traditional 3” steel spikes to obtain direct coupling. A 60-channel Geometrics StrataView seismograph recorded three vertically stacked impacts
from a 20 lb hammer on a 1 ft\(^2\) aluminum plate at each shot station. Single 4.5 Hz Geospace GS-11D geophones spaced 2 ft apart along all the profile lines (except at site 4) responded to frequencies from 5 Hz to 30 Hz. The source-to-nearest-receiver offset was nominally 24 ft and source-to-farthest-receiver offset was around 120 ft. This recording geometry and frequency range provided the optimum spread and data characteristics for examining earth materials between about 3 and 100 ft of depth at most sites.

**Data Processing**

Each 48-trace shot gather was recorded with live receivers in the optimum recording window. Multichannel records were analyzed with *SurfSeis* (a proprietary software package of the Kansas Geological Survey), facilitating the use of MASW with continuous profiling techniques. Each shot gather generated one dispersion curve. Care was taken to insure the spectral properties of the t-x data (shot gathers) were consistent with the maximum and minimum f-\(v_c\) values (\(v_c\) is phase velocities of surface waves) contained in the dispersion curve. Each dispersion curve was individually inverted into an \(x-v_s\) trace. Gathering all \(x-v_s\) traces into shot station sequence order results in a 2-D grid of the shear wave velocity field. The shear wave velocity field generated in this fashion does “smear” to a limited extent gradational velocity anomalies and requires an understanding of the overall resolution. The processing flow generally included the following steps:

- SEG-2 to KGS-modified SEG-Y
- Calculate the dispersion curve from phase velocity as function of frequency
- Estimate initial model (5 Hz to 35 Hz—15 to 250 ft wavelength)
- Invert to solve for shear wave velocity
- Contour velocity field (*SURFER*)

**Interpretation**

The 2-D shear wave velocity cross-sections have several striking characteristics likely influencing the hydrologic and structural characteristics of each site. Drill data acquired prior to the seismic survey helped optimize the recording parameters and confirm general lithologic interpretation of shear wave data based primarily on gradient and value of the shear wave velocity. Changes in material composition, cementation, or compaction are likely related to
rapid changes in the velocity gradient. Rapid changes in the velocity gradient and velocities values correlate quite well to lithologic changes and lithologies identified in boreholes drilled prior to acquiring the seismic data.

SITE 1—11427 61st St. North, Largo, FL

Seismic data for site 1 were collected along two parallel lines bounding the residence on the north and south (Figure 2). Existing data suggested subsidence activities are or have been active along the northeast side of the structure. Seismic profiles at this site started as far west as the street (61st St. N) right of way would permit, transgressing the northern property line, with both profiles ending at or near the street immediately east of the east neighbor’s property. Lines were deployed such that geophones in the road and on sidewalks were on plates. Spiked geophones were used in grassy and dirt areas, which made up about 80% of the receiver locations. An air conditioner was running for a few initial shots along the north side of the house, producing noise that was not a detriment, but it was turned off to minimize the background noise. When possible, geophones were planted in sod areas. The grass sod layer at most locations studied possessed a thick matted root system that has the potential to reduce or suppress ground motion, therefore decreasing the amplitude of recorded signal.

Processing of these data was consistent with the previous description. Data possessed a usable bandwidth of 5 Hz to 35 Hz, equating to a minimum and maximum depth of penetration around 5 ft to 100 ft, respectively. Data accuracy has been estimated to be about 15%, therefore changes in velocity of 300 ft/sec or more are significantly above the average error and relate to variability in geology. Since the contour interval was selected at 150 ft/sec, anomalies with closure on two or more contour lines are related to measurable changes in subsurface properties. Localized closures defined by a single contour may be real, but for the required level of certainty on this study they are considered background and used only to establish velocity trends. Velocity trends from line 1 are laterally consistent and likely suggestive of relatively uniform data characteristics, with smooth, continuous lateral and vertical changes in shear wave velocity.

Line 1

Line 1 is located along the north side of the residence with the first subsurface sample point near the northwest corner of the residence and the last near the corner of the pool in the
Figure 2. Map of site 1 at 11427 61st St. North in Largo, Florida.
neighbor’s backyard immediately east of this residence. Line 1 crosses over an area suspected to have subsurface conditions conducive to subsidence and possibly related to the structural damage observed at the residence. Shot locations occupied the western two-thirds of the line while subsurface sample points are from the middle two-thirds of the line (Figure 3). Line 1 was designed to place the northeastern corner of the house at or near the center of the imaged subsurface.

Geologic logs are consistent with the shear wave velocity field data. Considering the geology as logged and blow counts, it is reasonable to suggest that materials between the ground surface and about 10 ft of depth are vertically consistent. Between about 10 and 15 ft the blow counts increase quite dramatically, as does the shear wave velocity. The blow counts drop again between 15 and about 30 ft, corresponding to a distinctive drop in shear wave velocity. At 30 ft BGS blow counts increase, as does the shear wave velocity. A gradual increase in blow counts observed between about 30 ft and the bottom of the borehole is interrupted by a small zone around 50 ft BGS where the blow counts drop to 0. Interestingly, beneath station 140 a small isolated low velocity zone exists at about 45 to 50 ft of depth. Depending on the size of the anomaly encountered during the drilling of borehole SB-1, the shear wave velocity low at station 140 could be the drill-encountered soft zone at 50 ft.

Several features along this line are suggestive of anomalous earth. The layer truncation evident at about 15 ft of depth beneath station 140 is the most prominent and correlates to a drop in resistivity near the southeastern corner of the house (Figure 3). This feature can be interpreted as a subcrop of a stiffer, more resistive layer that has been replaced to the east by relatively low velocity and likely much more mobile materials. East of this wedge at 140 may be an area currently subsiding, as evidenced by lower velocity and therefore weaker materials. Looking a bit deeper, the “bedrock” layer is interpreted to be consistent with the 1350 to 1500 ft/sec contour interval. The shear wave velocity field imaged a bedrock surface with significant localized topography. These undulations in the bedrock surface are likely indicative of erosion. Of particular interest is the low velocity channel or incision between stations 80 and 100. This feature could be the result of dissolution of bedrock and subsequent subsidence of overlying materials. Two other bedrock low velocity wedges are evident beneath stations 140 and 185. These are smaller features along the two-dimensional plain of this survey but may increase in size laterally in other areas beneath this property.
Figure 3. S-wave velocity contours, site 1, line 1, 11427 61st St. North in Largo, Florida.
There does not appear to be a direct link between the bedrock the low velocity zones and the ground surface. Developing a unique pathway for subsidence materials to be transported downward from the surface would be very difficult with this data alone. However, both bedrock and near-surface anomalous areas do exist which could influence non-uniform setting of near-surface materials.

**Line 2**

Line 2 traces a west to east path from the sidewalk on the west side of the street (61st St. N) immediately west of the property to the street east of the adjoining east neighbor’s property (Figure 4). This profile runs parallel to and about 30 ft north of 114th Terrace. Subsurface sampling along this line extends from about 25 ft immediately west of the southwest corner of the residence to near the southwest corner of the backyard neighbor’s swimming pool. The line passes directly over an anomaly identified on resistivity data and within 10 or so feet of a second. Boring SB-1 is located, for all practical purposes, at station 100 or so on line 2 (Figure 4). Comparing boring information with the shear wave velocity field, several apparently significant boundaries (as identified by blow counts) correlate reasonably well with high gradient zones on shear wave zones. Lithologically the unit identified as Marl is characterized by relatively low blow counts and seems to correlate with the low velocity zone 20 to 30 ft beneath station 100. Sand identified in drillers’ logs between the ground surface and about 15 ft of depth varies by over 50% in stiffness as measured by blow counts. This variability is evident on the shear wave profiles. Gradual changes in velocity from 100 ft/sec to about 600 ft/sec from about 5 ft down to 10 ft, and then from 10 ft to 15 ft represents significant increase in velocity (100%) that appears consistent with a 100% increase in blow counts. Changes in velocity seem to track the subsurface material properties lithologically, mechanically (blow counts), and acoustically.

Absolute velocities for sands, silts, and clays at this site are as high as those observed in limestones at other sites in the general area. This extreme variability in velocity for a given lithology makes interpreting geologic units or layers based on velocity only possible within very localized areas. It is also interesting to note the lack of correlation between absolute velocity and blow counts (which should be indicative of stiffness). In general, trends in velocity seem to match up reasonably well with trends in lithology and structural competence (as measured by blow counts).
Figure 4. S-wave velocity contours, site 1, line 2, 11427 61st St. North in Largo, Florida.
SITE 2—1316 Kennywood Dr., Largo, FL

Subsurface coverage beneath the residence at site 2 was restricted by the drainage canal along the western property line. Apparent structural damage extended from near the center of the house to the western edge of the pool area. With access difficult and critical coverage limited at the western extreme of the property, it was not possible to extend the coverage as far west as optimum for the objectives at this site. Lines 1 and 2 intersected immediately east of the house, providing a high quality tie between the two profiles (Figure 5). Line 1 started about 40 ft east of Kennywood Dr., proceeding west across the asphalt road and grass-covered front yard (Figure 6), through a window in the front of the house (Figure 7), out through a sliding glass door near the pool (Figure 8), and finally past the pool to the edge of the drainage ditch (Figure 9). This line placement put the majority of the visible structural damage in the eastern portion of the house with the subsurface sampling aperture. The residence immediately south of site 2 possesses subsidence damage previously confirmed to be related to dissolution. Variability in floor coverings coupled to throughout the house seemed to have little effect on the continuity or quality of the calculated dispersion curves. It was necessary to use spike-mounted geophones for most receiver stations in the yard, while plate-mounted geophones were necessary on asphalt surfaces, cement driveways, and inside the house in the carpeted living room, tiled pool area, and cement deck.

Surface wave data from site 2 possessed a usable frequency band from 5 Hz to 30 Hz. Considering target depths and near-surface materials, these frequencies sampled materials from 7 ft down to 80 ft BGS. Non-source noise at this site originated from air conditioning units, electrical transmission lines, vehicles, and aircraft. Geologic logs and mechanical testing from five different borings all seem to agree that a hard and possibly cemented clay exists at around 30 ft with varying concentrations of sand, clay, and silt dominating the upper 50 ft. It would be quite speculative to attempt correlating lithology between borings from drill data alone.

**Line 1**

Line 1 provides a glimpse of the subsurface from about 20 ft outside the east wall of the house to about 5 ft east of the pool deck. Subsurface sampling was controlled by line placement. For the most part, areas of critical interest were imaged sufficiently to begin formulating options as to the likelihood and potential source of the subsidence. Two very noteworthy features are
Figure 5. Map of site 2 at 1316 Kennywood Drive in Largo, Florida.
immediately evident on this profile: The first is an extreme high velocity closure about 30 ft beneath station 120; the second is a deep, well delineated bedrock velocity low beneath station 100 (Figure 10). These two features are likely related to subsidence activities beneath this residence. As on previous lines, the 1000 ft/sec contour generally follows the boundary between stiffer or more cemented sediments and shallower, more loosely compacted sediments. It is reasonable to interpret rocks below about 60 ft as limestone or weathered limestone based on velocity and general lithologic descriptions alone. Again, as on other lines from this study, it is not clear if the subsurface coverage is laterally extensive enough to extend completely beyond the bedrock feature(s) responsible for the subsidence activities that have produced structural damage at this residence.

Undulating high to low velocity features within bedrock are indicative of sub-parallel fracture systems or localized dissolution features likely present in areas with less resistant rock or localized pockets of rock that are more susceptible to dissolution. Considering that the bedrock velocity pattern starts at the extreme east portion of the section where the bedrock velocity starts out quite low, then transitions into a zone of high beneath station 80, a low beneath station 100, a high beneath station 120, and then a low beginning that may center around station 140, it seems reasonable to suggest this pattern is consistent with unique fracture lineaments or blocks. A 3-D image of the bedrock in this area appears to have a dissolution pattern resembling swiss cheese. The extent of this cyclic pockmark type topography on the bedrock surface is difficult to suggest with any confidence due to the limited extent of this profile line.

Probably the most glaring anomaly is the extreme high velocity closure located beneath station 120 at a depth of around 30 ft or so. The extent of this feature, both vertically and horizontally, conclusively rules out any possibility that this might be an artifact associated with the technique. This closure resembles some kind of erratic located 20 ft or so above rock with a similar shear wave velocity. Knowledge of the three-dimensionality of this feature would greatly reduce the number of potential explanations for this anomaly. At this point it is left to speculation, with the most likely explanation involving some kind of erosional erratic deposited at or near the time the harder/more cemented clay layer was laid down. Another possibility that would appeal to the need to correlate surface subsidence and subsurface voids implicates this high velocity zone as the increased strain associated with bridging over a void. If that were the case, collapse and subsidence of overlying sediments in this area is a certainty. Upward
Figure 10. S-wave velocity contours, site 2, line 1, 1316 Kennywood Drive in Largo, Florida.
projection of the high velocity zone makes it similar in a lot of respects to the chimney type features observed beneath site 2.

**Line 2**

Oscillations observed in the shear wave velocity field at depths greater than 50 ft are consistent with changes observed in other areas around the southeast United States with active dissolution of limestone (Miller and Xia, 1999b). The frequency of the highs relative to lows on this south to north line is about 30 ft per wavelength (Figure 11). Considering the residence immediately to the south has damage that has been confirmed to be the result of dissolution subsidence, it is reasonable to suggest the low velocity zone at the extreme southern end of the line is related to confirmed subsidence. Based on that correlation, the features at stations 115 and 140 are strong candidates for dissolution anomalies. Little can be deduced from changes in the shear wave velocity at depths less than about 25 ft. It is not possible with this data alone to infer a migration path between the two “bedrock” dissolution features at stations 115 and 140 with surface subsidence and the resulting documented damage. Without a doubt, these 50% drops in the shear wave velocity field across lateral distances on the order of 15 ft are related to changes in the structural integrity of the rock units present below 25 ft.

Valuable data for correlating geologic properties with anomalous changes in shear wave velocity could be obtained if borehole MB-1 could be extended below the 30 ft hard zone identified on logs to a depth of around 65 to 70 ft. Boring MB-1, as best it can be located from the log itself, is at approximately station 140. Lithologic units and blow counts as described are consistent with the shear wave data through the depth range of the boring log. Shallow sediment velocities along line 2 provide little in the way of characteristics consistent with chimneys or conduits for subsiding materials working their way downward from the surface or very shallow near-surface. A couple higher velocity zones present north of station 120 are likely related to the concrete slab that makes up the driveway and sidewalk.

**SITE 3—2016 Golfview Dr., Dunedin, FL**

Two intersecting lines were acquired at site 3 (Figure 12). Line 1 was an east-to-west line starting east of Golfview Dr., crossing the street, entering the house through the front door (Figure 13), and then exiting the house through a sliding glass door that opened onto the pool
Figure 11. S-wave velocity contours, site 2, line 2, 1316 Kennywood Drive in Largo, Florida.
Figure 12. Map of site 3 at 2016 Golfview Drive in Dunedin, Florida.
deck (Figure 14). Line 1 exited the property through a hole in the fence, extending 40 or so feet into a vacant lot adjoining the west property line. Line 2 was a northwest-to-southeast line intersecting line 1 just outside the sliding glass doors near the edge of the pool. The line started in the far northwest corner of the property and ended just across the property line in the extreme southeast corner of the lot. Observed damage to the house was most pronounced along the eastern half of line 1 and 40 ft or so off-line from the center of line 2.

Surface wave data from site 3 possessed a usable frequency band from 5 Hz to 30 Hz, which, considering the target depths and near-surface materials, should provide high confidence measurements of materials from 7 ft to 80 ft BGS. All receivers located inside the house were outfitted with plate style ground coupling attachments. It is not possible to distinguish from the data alone which receivers were deployed with conventional spikes versus those with plates. To insure minimal damage to property, no shot points were recorded inside the house. Due to the reciprocity of the process, shotpoints were recorded up to the front door by pushing the spread, and then from just beyond the pool area across the west property line the spread was drug behind the source. This acquisition geometry allowed a continuous image to be obtained from beneath the house. Line 2 required plate-geophone coupling on about the 10% of the line across the pool deck. Data should allow detection of non-uniform changes in the stiffness of the near-surface materials under the house.

**Line 1**

Two features on line 1 might be significant to the subsidence-related damage inside the house at this location. First are a pair of high velocity closures beneath stations 110 and 120 (Figure 15). These closures seem to only correspond to the shallowest sediments (upper 5 ft), suggesting a strong relationship to the cement pad and/or immediate subgrade. These high velocity zones resemble closures occasionally observed when bridging is present above void areas associated with mines or dissolution features. It would be most logical to suggest the cement pad in this area is not uniformly supported by the subgrade, causing higher shear wave velocities, and which is likely related to increased strain resulting from separation of subgrade from the cement pad. A low velocity zone within “bedrock” at 60 to 80 ft beneath station 93 or so is likely related to these near-surface high velocity closures and represent the second feature on this line that might correlate to subsidence activities.
Figure 15. S-wave velocity contours, site 3, line 1, 2016 Golfview Drive in Dunedin, Florida.
This deeper feature is probably the root or source of and at minimum related to the shallow subsidence responsible for the non-uniform settling of near-surface sediments and associated damage to surface structures. This low velocity zone clearly indicates stiffer or more competent rock present at 70 ft or so BGS on the western end of this profile is altered on the eastern end. It is not obvious how the shallow high velocity closures tie back to the deep velocity low in bedrock; it is possible that outside the two-dimensional plane of this survey a conduit exists connecting these two features. Key to correlating these two features would be obvious changes in the larger gradient zone at the base of the low velocity layer around 15 ft BGS. A higher velocity slice seems to extend between about 20 ft and 50 ft beneath about station 100 that might be associated with any commonality the deeper low velocity and shallow high velocity anomalies might possess.

Of secondary interest to this particular site, but possibly a key component of the overall study, is the indication of high velocity sediments present at depths as shallow as 20 ft at the extreme western end of line 1. This observation supports the possibility that the surveyed area might be well within the disturbed subsurface affected by dissolution activities. If this is the case, the degree of disturbance diagnostic of subsidence observed on the seismic profiles between the dissolution feature interpreted at the bedrock surface and subsidence observed at the ground surface could have an extremely low signal-to-noise ratio. The very non-linear nature of the velocity gradient within the sampled subsurface could be characteristic of subsidence activity in this geologic setting.

**Line 2**

It can be postulated that the spurious high velocity anomalies scattered throughout the subsurface as sampled by line 2 are possible characteristics of subsidence-prone areas in this geologic setting. High velocity anomalies observed beneath stations 120 and 130 are curiously similar to those observed on line 1 at depths of less than 5 ft (Figure 16). Extrapolation of these shallow high velocity closures between the lines would correlate to a linear feature approximately matching structural damage observed in the house foundation and walls. Also of interest is the high velocity chimney features that appears to extend from the interpreted bedrock at 50 ft or so up to the southeastern most high velocity closure located beneath station 130. Previous studies, however, have always correlated low velocity zones to dissolution areas or evidence of
Figure 16. S-wave velocity contours, site 3, line 2, 2016 Golfview Drive in Dunedin, Florida.
subsidence. This high velocity chimney suggests stiffer or more competent material is present in this very vertical, distinct feature. Drilling into and around these high velocity anomalies would provide valuable information for improving correlation and the general understanding between shear wave velocity and material properties.

Line 2 has several features that are particularly alluring to speculation about localized changes (possibly abrupt) in the physical properties of the near surface. Included on that list are the pronounced high at about 15 ft of depth beneath station 110, the high over low velocity closure pair beneath station 75 at depths from 20 ft to 45 ft, a small high velocity closure at 30 ft of depth beneath station 95, and the hint of a substantial high-velocity closure over low-velocity closure at the extreme southeastern end of the profile. The low beneath station 125 is not particularly unique in terms of its location or velocity, but the fact that it is totally surrounded by high velocity closures would suggest a somewhat unique setting. These features are all intriguing, but interpreting them with any degree of certainty requires ground truth.

Drill data from this site lack solid evidence supporting significant lateral (sitewide) continuity in lithologic units. With the exception of the transition from sand to a green/gray sandy clay or clay at 8 to 10 ft and sporadic lost circulation zones between 15 ft and 35 ft of depth, lithologic descriptions are not sufficient to make unique ties between material described in the wells. With the variability in material properties and measured stiffness documented in drillers’ logs, it is no surprise the shear wave data have the extremely variable and almost chaotic nature observed across most of the profiles. It is most likely the 1000 ft/sec contour roughly correlates to the shallowest observations of “limerock,” “limey clay,” “clayey limestone,” and “lime mud.” The lower velocity materials (i.e., less than 450 ft/sec) appear to be predominantly sands, with clays represented by velocities from about 600 to 1000 ft/sec, and velocities greater than 1500 ft/sec likely related to reasonably competent limestones.

**SITE 4—4118 Star Island, Holiday, FL**

Due to site access limitations, it was not possible to tie the two lines through direct intersection (Figure 17). The lines ran parallel to each other and were separated by about 15 ft. Line 1 paralleled the east side of the house as close as was possible without getting into foundation materials. Line 2, on the other hand, was deployed directly through the center of the house, entering through the front door (Figure 18) and exiting through a bedroom window in the south
Figure 17. Map of site 4 at 4118 Star Island in Holiday, Florida.
exterior wall of the house (Figure 19). Since drilling at this site detected “bedrock” at depths less than 30 ft, it was determined necessary to decrease the station spacing and source-to-first-receiver offset. This change allowed optimization of the recorded data within the depth range of 4.5 to 40 ft. Penetration depths of the surface wave depends on wavelength—a function of frequency and velocity; however, recording the appropriate surface wave for the depth of interest depends on equipment and acquisition geometry.

This was the only site that required the seismic source to be operated inside the residence (Figure 20) and receiver and source spacings and offsets needed to be reduced by half (Figure 21). With the most significant structural damage along the south wall and southeasternmost rooms in this residence, it was critical that subsurface sampling extend as far south as possible. A physical limit to the southernmost sample point for both lines was dictated by the canal, which marks the southern extreme of the property and the limit of usable ground. Since receivers extend beyond the subsurface sampling by a distance equal to half the spread, for these lines it was not possible to image the subsurface any closer than about 24 ft from the canal retaining wall, putting the southernmost image point about 5 ft from the outside south wall. In general, the velocities measured at this site are consistent with those measured at equivalent depths at the other sites that comprise this study.

**Line 1**

Shear wave velocity contours from line 1 possessed the most uniform gradient observed during this study. Consistent with the other profiles from this area, a velocity inversion is evident between 5 ft and about 12 ft BGS on the northern end of the profile (Figure 22). A higher velocity gradient between 12 ft and 21 ft can be correlated with some degree of confidence to the sandy clay at 13 ft to 15 ft in borings SB-2 and SB-3. Exact identification of the sandy clay interface is not possible with contoured shear wave data due to relatively small increases in shear wave velocity routinely observed across even the most distinct lithologic boundaries in unconsolidated sediments. However, the 100% increase in shear wave velocity across a vertical distance of about 7 ft is a strong indication in this area of a significant change in material. Consistent with other data from this area, the 1000 ft/sec contour is likely representative of what has been identified on log data as “bedrock” or at least where the auger encountered refusal.
Figure 22. S-wave velocity contours, site 4, line 1, 4118 Star Island in Holiday, Florida.
Little in the way of significant anomalies or features appear evident above about 20 ft or so, below 20 ft however there does appear to be a pronounced velocity low in the bedrock beneath about station 50. This low is similar in character to sub-bedrock features observed on other profiles from this area. It appears to be much less abrupt than others and likely indicative of paleoactivity. Evidence in support of the paleotheory on this feature includes not only the subdued expression of the feature, but also the apparent drop observed in the shallower sediments. This is one of the few features it appears possible to extrapolate observed subsidence from depth (25 ft in this case) to within 5 ft of the surface. Projecting from beneath station 45 upwards from 25 ft to beneath station 40 at 5 ft is the gradient of the depressed velocity contours. The apparent evidence of subsidence traceable from “bedrock” to very near the surface is critical if confirmed through drilling to improved interpretations of active subsidence features at other sites in this area.

**Line 2**

This profile was the only one requiring operation of the source inside a residence (Figure 23). Several very interesting features, possibly indicative of subsidence in this area, can be interpreted at depths ranging from 5 to 40 ft along this line (Figure 24). “Bedrock,” which is equated to the 1000 ft/sec contour, is represented by a much higher gradient along this line, indicative of a more abrupt change in velocity. Above the 1000 ft/sec contour are a couple distinctive features that likely relate to the structural integrity of the rocks at this site. Speculation into their significance to the overall geology at this site is based on lateral variability in the velocity structure and localized velocity nodes. First, the high velocity closure at about 8 ft of depth beneath station 62 is quite explicit. It has a different appearance and general orientation in comparison to the high velocity feature apparent above “bedrock” on line 1 at site 2. This feature is more elongated with a significantly lower maximum velocity and smaller gradient than the one on line1, site 2. It is interesting to note that this high velocity anomaly seems to displace the velocity inversion downward, represented by the blue zone (200 ft/sec contour). There appears to be a truncation and offset in the low velocity inversion zone beneath station 77. This sets up a scenario suggesting subsidence occurred around station 65 at a depth of 5 ft to 10 ft with connection to the near-surface near station 85.
Figure 24. S-wave velocity contours, site 4, line 2, 4118 Star Island in Holiday, Florida.
The prominent bedrock low beneath station 85 provides the necessary destination for materials that have slumped or collapsed into dissolution voids or under compacted zones. If the low velocity zone beneath station 85 is indicative of dissolution and subsidence, the apparent offset beneath station 75 could be from roof failure when the span of unsupported materials extended beyond what could be supported. This slumping/collapse would in turn destabilize the near-surface sediment sufficiently to allow surface subsidence to occur, eventually resulting in the damage apparent in the walls of the residence. One segment of that potential series of events, yet to be explained, is the presence of the high velocity zone extending from station 50 to station 75 and centered at about 7 ft BGS. This feature is consistent with most void areas observed in previous studies. Routinely a void area will be represented on shear wave data as an anomalous high velocity closure, inferred to be indicative of increased strain across an undersupported roof span. If the previous inference is a true representation of the geologic situation at this site, it is quite possible to see as much as 5 ft of subsidence at the surface once all the materials have reached a static state.

SITE 5—5538 Frances, New Port Richey, FL

Due to surface obstacles and a narrow lot, profiles were acquired along parallel transects immediately adjacent to the north (line 2) and south (line 1) sides of the house (Figure 25). Both lines began on the extreme west side of Frances Street, paralleling the long dimension of the house and as close as possible to the house, past the pool area, and ending at the edge of the canal. This orientation provided the best subsurface coverage in the areas where structural damage was most pronounced. Borehole geology from this site seems a bit unique in comparison to other borehole data studied on this project. Blow counts seem significantly lower on the average than those measured at the other 5 sites. This suggests minimally stiff materials were encountered by drilling in the upper 60 or so feet, which is consistent with the apparent slowness of the inverted shear wave velocity values observed along line 1 and line 2. Velocities measured at this site are 50% or more slower than those on any other line. Strangely the borehole logs from this site identify a limestone layer around 30 ft, which seems less competent than some of the silts and clays encountered at other sites. Comparison of the boring logs at this site with those from other sites clearly indicates the individualism of each site as it relates to selection criteria for subsidence classifications.
Figure 25. Map of site 5 at 5538 Frances in New Port Richey, Florida.
Surface wave data from site 5 possessed a usable frequency band from 6 to 23 Hz. Considering the target depths and near-surface materials, these frequencies should have provided a high confidence measurement of materials from 8 ft to 80 ft BGS. Since both lines were across the lawn, all the receivers were deployed with conventional spikes at site 5. To insure minimal damage to property, no lines were acquired that required access to the inside of the residence. Surface wave data from this site should reveal how well the method can detect non-uniform changes in the stiffness of the near-surface materials in close proximity to the long axis exterior walls of this house.

**Line 1**

Structural damage is evident along the south side of the residence. Since it was not possible to extend line 1 into the house, line placement was as close the south wall as possible and along many parts of the line the recording stations were beneath the footprint of the balcony. The most noticeable damage to the outside wall of the house was near the southwest corner. Evident on the surface wave contour of line 1 is a series of closure-style anomalies that extend down to a depth of around 30 ft beneath station 100 (Figure 26). This high velocity near surface is suggestive of increased strain, much like that expected if near-surface loading were excessive in this area. The low velocity zone (blue) is present here as at most sites studied in the Tampa area. Continuing vertically downward from the blue zone, a distinctive high over low velocity closure setting is clearly evident. This velocity pattern is distinctive and has been synonymous with subsidence-prone areas. Velocity characteristics beneath station 100 are very suggestive of an area with significant subsidence potential.

Continuing downward beneath station 100, no destination can be confidently located for materials that may collapse or have collapsed from near-surface layers beneath station 100. Moving 15 ft to the west, however, is a likely key to the subsidence activity along this portion of the house: An apparent deep gouge in the bedrock defined by the low velocity zone centered on station 85 between about 40 and 65 ft BGS is quite evident. It is interesting to note that the bedrock surface defined by the 1000 ft/sec contour is 20 to 30 ft higher on the south side of the house in comparison to the north side. This topographic change in bedrock supports a scenario where the north side of the house is within a paleosinkhole which has long since filled, while the south portion of the house, as far as its southern wall, is outside the sinkhole. The dissolution
Figure 26. S-wave velocity contours, site 5, line 1, 5538 Frances in New Port Richey, Florida.
edge of the sinkhole could be as far south as the edge of the southern house foundation. If this is the case, subsidence activity will be focused along active dissolution edges present along the perimeter of a reactivated paleosinkhole. It is quite likely this house sits on or very near a lineament marking the active dissolution front.

**Line 2**

A single borehole located very near station 75 TD’d at a depth of around 60 ft. The borehole was terminated when it encountered “rock” as specified on the drillers’ log. Correlation between the drill-defined bedrock and 1000 ft/sec contour (used as the bedrock standard on previous lines) is quite excellent. As previously noted, the velocity structure on this line is significantly different than any of the other five sites studied. Of particular interest on line 2 is the low velocity zone that appears to have penetrated the bedrock surface beneath station 120 (Figure 27). This low velocity feature is offset about 10 ft horizontally and 15 ft vertically from a shallow high velocity anomaly which may be from outside the 2-D plane. If these features are related, they form a very distinctive chimney-like structure consistent with a reasonable geologic interpretation.

If this high-velocity shallow anomaly and low-velocity deeper/bedrock anomaly are related, it is reasonable to suggest they are subsidence features that formed when native near-surface sediments subsided into deeper dissolution voids. Assuming this low velocity zone in bedrock is from subsidence materials that filled a dissolution void, it is also reasonable to suggest that the slump/offset in the low velocity layer at around 10 ft BGS is the result of roof collapse after the dissolution void got larger than the material could support. This failure allowed surface and near-surface materials to fill in the void. Under that scenario, lower velocity material above bedrock replaced dissolved bedrock, which then left the low velocity anomaly beneath station 120. This process propagated to the surface, with shallower sediments filling holes left as deeper materials collapsed or slumped into the hole originally formed by dissolution within bedrock. This process could easily have resulted in the high velocity slice in the otherwise continuous low velocity (blue) layer and the lower velocity materials (green) fill present within the higher velocity bedrock materials (yellow and orange).
Figure 27. S-wave velocity contours, site 5, line 2, 5538 Frances in New Port Richey, Florida.
SITE 6—1677 Pinewood Dr., Clearwater, FL

Surface obstacles made effective deployment of the lines a challenging task. With most obvious structural damage in the southernmost room of the house, two cross lines that intersected immediately outside the house adjacent to the southernmost room maximized the density of subsurface samples near the most damage area (Figure 28). Line 1 started across the north/south street that marked the east property line, crossed under the wood fence, behind the house along a crack between the patio and house foundation, exited the property through the board fence along the west property line, and ended several 10s of feet onto the adjoining property (Figure 29). Line 2 began on the north side of Pinewood Dr., crossed the front yard (Figure 30), entered the house through the front door (Figure 31), proceeded through the house (Figure 32), out a back window, alongside the pool (Figure 29), through the south property fence, and ended within 4 ft of the south neighbor’s house foundation. This orientation provided the best subsurface coverage in the areas where structural damage was most pronounced. Borehole geology provides a very consistent picture of the prominent lithologic interfaces around this site. Most noteworthy is the hard clay at around 22 to 25 ft. This layer has a consistent geologic description and stiffness (based on blow counts) in all five borings from this site. In general, this extremely hard layer appears to be consistent with the 1000 ft/sec contour interpreted to be “bedrock” at the other sites that make up this study. All five boreholes TD’d in a limestone layer at about 60 ft BGS. This is likely indicative of the higher velocity gradient somewhere between the 1800 ft/sec and 2000 ft/sec velocity contours. Shear wave velocity data appear to correlate quite nicely with the prominent geologic interfaces encountered in the boreholes around this site.

Surface wave data from site 6 possessed a usable frequency band from 7 to 25 Hz. Considering the target depths and near-surface materials, these frequencies should have provided a high confidence measurement of materials from 11 ft down to 75 ft BGS. Some of the receivers deployed at site 6 were outfitted with conventional spikes, however many areas, such as around the pools, along the sidewalks and patios, and especially inside the house required conversion to the steel baseplates. To insure minimal damage to property, no lines were acquired that required source access to the inside of the residence. Surface wave data seems to have the potential to allow detection of any significant changes in the stiffness in the areas that appear to have been affected the most from subsidence near the south side of the residence.
Figure 28. Map of site 6 at 1677 Pinewood Drive in Clearwater, Florida.
Line 1

Line 1 has three features that are worth considering anomalous and possibly related to subsidence at this site. A shallow offset feature in the low velocity zone about 10 ft beneath station 105 appears geometrically consistent with features on other lines interpreted as chimney or down drop layers associated with roof failure (Figure 33). Also above “bedrock” is a low velocity closure which seems localized, having a shape that could be result of downward movement of sediments replacing more compacted/competent material with less compacted materials from shallower layers. The third feature of interest is located below the 1000 ft/sec contour and characterized by significantly depressed velocities which appear consistent with features on other lines interpreted to be related to dissolution. Clearly, a direct conduit for fluid or sediment movement cannot be identified on this two-dimensional profile alone, however it is likely to expect the actual connection between bedrock and ground surface to follow a very meandering path of least resistance.

Probably most significant to subsidence in this area is the bedrock anomaly beneath station 77. This anomaly could be the destination for most shallow sediments moving downward from their originally deposited locations. Considering the location of surface structural damage and the upper 20 ft of data on this profile, the chimney feature beneath station 100 is key to subsidence damage observed in the south portion of the residence. It is not nearly as clear how the low velocity anomaly at about 30 ft below station 125 affects the current subsidence system. If the feature at 10 to 20 ft is characteristic of subsidence and is part of the mechanism responsible for the uneven settling of the ground surface, it would take a significant number of boreholes to eventually encounter this 5 ft or so wide disturbed zone.

Line 2

Acquiring data with receivers deployed inside the house seems to have had no impact on the overall data quality or interpretability. A bedrock low located beneath station 70 could be an edge effect or remnants of bedrock dissolution activity at or near the north side (front) of the house (Figure 34). Some skepticism is justified in interpretations between about stations 70 and 75 based on the dramatic variations in velocity structure at that extreme end of the line. Focusing interpretation on the southern three-quarters of the profile permits higher confidence correlations between the velocity field and geologic features or properties. The velocity field below
Figure 33. S-wave velocity contours, site 6, line 1, 1677 Pinewood Drive in Clearwater, Florida.
Figure 34. S-wave velocity contours, site 6, line 2, 1677 Pinewood Drive in Clearwater, Florida.
about 30 ft is variable, but not anomalous to the point that dissolution related features were a probable interpretation.

Within the upper 20 ft between stations 100 and 145 a couple of subtle features might be indicators and possible characteristic of subsidence activity at this site. A high velocity chimney, not nearly as pronounced but similar in configuration, character, and location to the one observed on line 1 at this site, is evident beneath about station 137. It is quite likely these features (one on line 1 and the other on line 2) are related and even possible that they are the same feature. If they are the same feature, some degree of three-dimensionality can be ascertained from these data when interpreted coincidently. The second shallow feature of interest is located beneath station 115 at about 5 ft BGS. This high velocity closure on line 2 is located at about the same depth and offset from the chimney feature as it is on line 1. The velocity values are extremely similar and the gradients are consistent. Looking at these two shallow features that appear on both lines 1 and 2, it is not unreasonable to suggest they are related and somehow play a role in the subsidence at this site.

Correlating shallow features along lines 1 and 2 provides reasonable support for suggesting that the high velocity chimney feature located beneath 137 on line 2 and 105 on line 1 are related. This feature may be indicative of the edge of a large active subsidence zone fueled by the dissolution activities at or within bedrock as suggested on line 1 beneath the eastern end of the profile. If this scenario is consistent with the dissolution mechanisms and processes in this area and supported by drilling, it is reasonable to suggest this house is on the northwestern edge of a larger subsidence feature that could easily affect a substantial number of houses along the trace of the high velocity chimney feature.

Conclusions

Shear wave velocity field data provide some degree of insight into the subsidence history of each of the six sites investigated. Consistent among all sites was the presence of a low velocity zone vertically elongated within the portion of the section identified as “bedrock.” It is reasonable to infer this feature to be somehow related to the actual dissolution of bedrock materials. Also present on each line was a pronounced velocity inversion at a depth of around 10 ft. This low velocity zone as well possessed features indicative of subsidence. Chimney features
with high velocity material slicing into lower velocity layers seems to be consistent with a possible conceptual model for the dissolution and subsidence activities in the Tampa area.

One possible dissolution and subsidence scenario supported by almost all the surface wave data collect in the Tampa area involves dissolution within a localized area of the bedrock (occasionally associated with a paleosinkhole), followed by several meandering chimney type features that formed as sediments gradually subside, layer by layer, into the void left after the collapse and subsidence of the layers directly below.

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References


