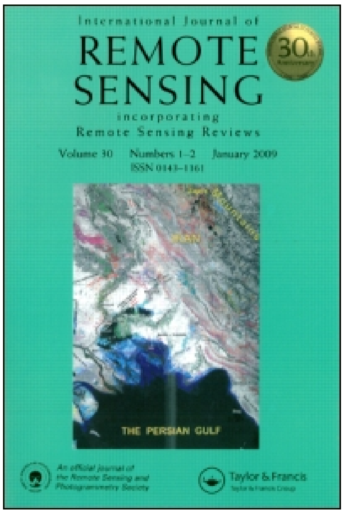

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Topographical mapping in littoral regions using the GPS backpack tideline tracing skill

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Topographical mapping in littoral regions using the GPS backpack tideline tracing skill

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Inter-tidal zone survey methods are varied and have progressed with the advancement of survey technology. The most significant features of a method are its restrictions on the topography to which it can be applied and the efficiency of the transition from fieldwork to processing or mapping of the dataset. This paper provides details of a GPS backpack method, indicates it is well matched with the altitude measurements obtained by the real-time kinematical positioning technique, and contrasts it to the use of echo-sounders when the littoral zone is submerged. A comparison of the results obtained by the tideline tracing method, varying by at least 20 cm, indicates that echo-sounder measurements were less accurate with poorer resolution, and more laborious in mapping the topography of the littoral region. In the inter-tidal zones inside Taichung Harbour and off the Pali coast, where gentle beaches have wide, flat low tide terraces crossed by a series of longshore bars and runnels, the tideline tracing method successfully provided topographical data on the centimetre scale. This method sampled denser data points distributed on the local slope, such as the slopes off the berm and the terrace in Taichung Harbour being all clearly defined with the gradients around 3–7°.

1. Introduction

Traditional survey methods use sounders in the inter-tidal zone (ITZ) in the period of high tide while the ITZ is submerged, or employ lasers or the Global Positioning System (GPS) in low tide periods while the beach face is sub-aerial (George and Guillard 2003, Freeman *et al.* 2003, 2004). Generally, they are equipped with the real-time kinematical positioning technique (RTK) differential global positioning system (DGPS), measuring terrain heights by running survey lines one by one, or by tracing tideline on the beach to estimate topography by working on specific targets, like high angle sand dune or cliff. However, they may be inaccurate as well as laborious in mapping the topography of the ITZ in littoral region.

In larger-scale surveys, air photography or satellite imaging can be useful, especially because of their efficiency (Mason *et al.* 1999, Roberts and Anderson 1999, Stumpf and Holderied 2003). Their accuracy can suffer due to the difficulty of determining the orientation of the resulting photographs of the sea without the inclusion of expanses of shore marked by targets to indicate orientation. In addition, the cost is expensive if the survey area is not expansive enough.

There are multiple ITZ survey methods, as they have progressed with advancement of survey technology, so in order to choose the most suitable method,

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the purpose of its application must be considered (Davis 2004, USACE 2002). ITZ survey methods can be categorized into two major types: remote sensing and direct survey. Remote sensing methods include air photography, LIDAR and echo-sounders. The direct survey methods generally use the rod transit and the backpack, which can be carried by people, or by vehicles such as the CRAB (Coastal Research Amphibious Buggy), the ATV (All Terrain Vehicle), boat or sled (table 1).

However, all these methods have their own limitations. Many studies have focused on the correlation of different survey methods conducted with remote sensing, and the resulting data have been checked for accuracy by comparing to data collected by the direct method (Irish and White 1998, Irish and Lillycrop 1999, Stockdon *et al.* 2002, Manizade *et al.* 2003). Air photography analysis and the LIDAR method are most efficient in large area surveys, but they all require calibration by a true geo-reference in order to achieve sufficient quality and correlation of datasets. Sounding surveys have sometimes been included to play the important role of calibration.

Facing an open sea, beaches are merely piles of loose sand quickly adapting their shape to changes in wave energy. The beach is therefore able to maintain itself in a dynamic equilibrium with its environment. If air photography or LIDAR are not used, topographical surveyors usually observe the beach and recreate a map of its shape by assembling profiles that run at right angles to the shore line, so it is not possible to provide precise 2D morphological definition (Parson 1997).

In recent years, use of the GPS real-time kinematical positioning technique (RTK) has been prevalent (Freeman *et al.* 2004). However, in the littoral zone, RTK has been conducted by running a number of longitudinal lines evenly, and it is necessary to march on the beach with a navigator. In addition, the surveyor needs to maintain the altitude of a GPS antenna at a fixed location. Although air photography or satellite imaging can be useful in large-scale surveys, considering the coverage of data distribution, to deliver a more user-friendly, cost-effective method in a relatively small region, topography on the centimetre scale in the ITZ area using a backpack tideline tracing method will be demonstrated. With this proposed method, everyone who carries a C/A (coarse acquisition) coded GPS can obtain topographical elevations at cm-scale accuracy.

2. Survey methods

A wide variety of troughs and ridges may appear on beach profiles, and beach gradients can vary between 0.2 (11°) and 0.01 (0.5°) (Pethick 1984). As a result, the complicated morphology of beaches, especially in the littoral zone, makes them difficult to map in detail either by echo-sounding or by land surveying. Steep beach profiles usually possess a marked landward ridge called the berm, which forms at the upper limit of the wave swash. This flat-topped feature may be mapped only by traditional land survey methods. Seaward off the berm, the profile follows the steeper beach face extending to the long-shore bar, which is just below the low tide level. Gentle beaches then have a wide, flat low tide terrace that is usually crossed by shore-parallel ridges and runnels.

The first survey was conducted in Taichung Harbour of western Taiwan, in which two undeveloped docking areas near South Pier and Central Pier as per plans were to be dredged deeper in 1996 (figure 1). At the time, there were three ITZ areas under investigation: South Zone, Central Zone, and North Zone, named for the sides of the terminals. Experimental surveying had been conducted inside the

Table 1. Classification of the ITZ methods.

	ITZ survey methods	Instruments used	Description	Baseline length	R/A/E/C/S*
Direct	Backpack tideline tracing	RTK/DGPS, or Total Station	The RTK DGPS and tracing tideline are used on the beach to estimate topography by walking/sledding, mainly on high angle sand dunes or cliffs (Freeman *et al*. 2004, Haxel and Holman 2004).	0–2 m	2/1/3/1/1
	Rod-transit	RTK/DGPS, or Total station	A rod is held on the beach surface, moving to each survey point; the rod position and height are obtained by Total Station or RTK DGPS to arrive at the beach profile. An alternative method involves towing a high tower called CRAB in deeper water (Parson 1997, Davis 2001, USACE 2002).	0–20 m	3/1/3/1/1
Remote Sensing	Inter-stereo photography	Camera or video	Topographical elevation is extracted and convoluted with the tidal height from inter-stereo images at a fixed high point (Plant and Holman 1997, Lohani and Mason 1999, Aarninkhof *et al*. 2003, Haxel and Holman 2004)	10–1000 m	2/2/2/1/2
	Airborne Multi-Spectral Image	CCD with scan camera	A fixed wing aircraft is equipped with a multi-spectral camera measuring water depth less than 2 m. This results in more detail than satellite images and is cheaper than the LIDAR system (Roberts and Anderson 1999).	300–500 m	1/1/2/3/3
	LIDAR (LIght Detection And Ranging)	Laser with DGPS/ RTK positioning	A green and infrared laser is used to detect water depths on the aircraft, by calculating the difference of the signal travel times between the water surface and the bottom. It is mainly limited by the turbidity of the water body to maximum depth of 80 m in the clear water column (Irish and White 1998, Irish and Lillycrop 1999, Guenther *et al*. 2000, Wozencraft and Irish 2000, Stockdon *et al*. 2002).	300–500 m	1/1/2/3/3
	Satellite Image	Passive CCD, or Synthetic Aperture Radar	Remote sensing of the coast and near-shore area by tracing the most clearly identified waterline on satellite images (Mason *et al*. 1995, 1998, 1999, 2001, Lohani and Mason 1999, Ryu *et al*. 2002, Lafona *et al*. 2004).	Satellite orbit height	1/3/2/2/2
	Echo Sounding	Echo-sounder with DPGS/RTK positioning	A sled, jet ski or small boat is equipped with an echo-sounder to estimate water depths in the high tide period in the near-shore area. This isthe most reliable water depth sensing method so far (USACE 2002, Freeman *et al*. 2003, 2004).	1–20 m	2/2/2/1/2

*R/A/E/C/S (Range/Accuracy/Efficiency/Cost/Simplicity); 1 for the best, 3 the poorest harbour primarily because the water mass was calm, not suffering from wave energy perturbation, and tides off the Taichung area were also large, ranging from 3 to 6 m.

In assessing the accuracy of the hydrographic survey relative to dredge measurement and payment, the survey results can easily impact the accuracy of dredge volume computation. These results are affected by the density of data coverage, especially when the terrain shows irregular bottom topography, and also by the errors in depth measurements. However, when areas are computed for single-beam cross-sections, large variations will occur if terrain irregularity exists between the sections, and larger volume errors will be induced if deviation of depth is observed. Normally, the survey is run with closer spaced cross-sections or with full-coverage multi-beam soundings. In Taichung Harbour, the dredged areas were mostly located in the littoral region where the multi-beam survey has been inefficient. Methods other than sounding were therefore considered.

The locations of the three zones are shown in figure 1. In the satellite picture, survey areas include sub-aerial regions, i.e. those that were unsubmerged during the lower stand level of tidal period, showing two trenches, one incised and one crossing, in the South Zone and Central Zone, respectively. The areas chosen for the survey each possess different morphological features. The North Zone exhibits a distinctly steeper beach face; the Central Zone features a wide area of mudflat beach floor (figure 2).

The second survey was conducted in 2005 in the near-shore area of the Pali coast of north-west Taiwan. The area possesses a gentle beach face having a wide, flat low tide terrace crossed by a series of shore-parallel bars and runnels, resulting in a complicated morphology in the littoral zone. Therefore, in addition to using the tideline tracing method on the area, one supplemental survey using RTK was necessary; the rod-transit method described in table 1 was applied to the beach surface during the neap tide period to get several beach profiles across shore-parallel bars and runnels.

Although the GPS device may be carried while riding horseback or aboard automobiles for tracing the water line on the beach, in implementing the backpack tideline tracing method, as the method title indicates, we relied solely on volunteers who backpacked with a C/A coded GPS to measure horizontal positions spatially by laboriously following the water line on surface of the beach. The GPS model was Ashtech Z-XII, and DGPS positions were solved by the AOSS software package. Terrestrial height was determined by tidal level in the geodetic system, and at a temporal instant the tideline or water line shown on the beach stands for a bathymetrical contour with the value defined by the reading of tidal gauge located in the vicinity. Thus, during the surveying, a Pacer tidal recorder, with initial accuracy of 2 cm, was deployed in the water on the north side of the Central Pier (figure 1), and the data sampling interval was set at 1 min.

The resulting positioning data downloaded from the memory card of the GPS was then processed using the AOSS package, providing DGPS positions of tideline throughout half of a tidal period. Each position can be matched with a height value on the clocks in the GPS and tidal gauge. The data distribution obtained by the backpack tracing method may display a pattern as shown in the inset of figure 1.

The tideline tracing method was used to position the water line while the tide was retreating to the sea. Apart from using the echo-sounder method to measure water depths during the flood tide period for comparison, the tideline tracing method was the primary method used to measure the topography to the littoral zones in this

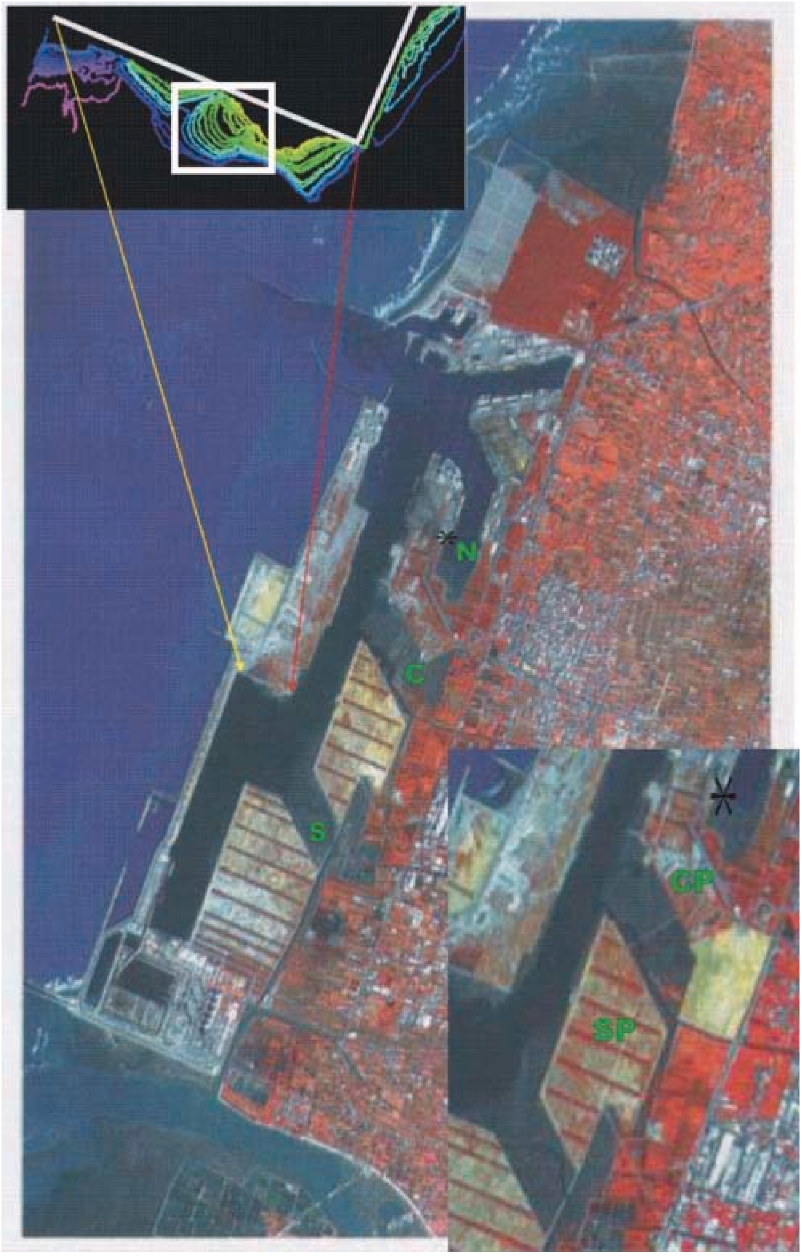

Figure 1. SPOT1 satellite pictures taken in the years of 1993 and 1995 (inset in lower right corner) in the Taichung Harbour area. An HRV sensor with 20 m pixel size was used. South Pier and Central Pier are indicated by SP and CP, respectively. The asterisk indicates the location of the tidal gauge deployed. The littoral areas of South Zone, Central Zone and North Zone are denoted by S, C, and N, respectively. In the littoral zones while pictures were taken, most areas were sub-aerial, and deeper trenches crossed the areas. The inset on the upper left corner shows the traces of the survey lines conducted by backpack tracing measurement in the location (a white square box defines the area in figure 5), delivering the terrain's altitude values in relation to tidal level. Its location in the harbour is denoted by a set of arrows.

Figure 2. Mudflat environment located in the Central Zone of Taichung Harbour, where small runnels appear in the location.

experiment. However, single beam sounding needed to be applied to the trench area in the area, which is always submerged in the water inside Taichung Harbour.

A hydrographical sounder ELAC 4100 was used when the areas were covered by seawater, and the transducer frequency was at 200 kHz. Survey tracks were kept at an interval as close to 20 m as possible; however, in order to increase the spatial coverage of soundings, the sweep sounding method was conducted (figure 3). There were two transducers connected with a transceiver of the ELAC 4100 echo-sounder, using a relay to trigger the transducers alternately. Every position with relation to each transducer was calculated using a GPS by a fixed length, and a defined vector with its bearing measured using a KVH compass at the time the acoustic ping was triggered sequentially. Therefore, along the ship track, there were two soundings separated by about 5 m in the direction normal to the track line (figure 4).

3. Results and discussion

3.1. *Taichung Harbour*

When the data obtained by the tideline tracing method was plotted (figure 5), it was characterized by the elevation contours following the traces of waterline. Therefore, as shown in figure 5, the runnels or ridges situated in the area can be recognized. In Taichung Harbour there was an approximately 3.5-m drop in sea level within six hours during a neap tide period. At this rate, the sea level would drop an average of 1 cm a minute, providing a resolution of the measurements in a centimetre scale. For instance, the squares shown in figure 5 share the values of elevations from 3.81-m to 3.82-m or from 3.71-m to 3.72-m of centimetre occupying a distance of about 50 m when a person carrying the GPS walked at an average speed of 3 km hr^{-1}.

Hence, once the survey can be conducted by using a beach vehicle, or even by riding a horse, 250 m can be covered in one minute. At this speed, surveys can be

Figure 3. Sweep beam echo sounder conducted in bathymetrical survey in the South Zone area. Two transducers, controlled by a relay box that was connected to an echo sounder, were fastened to the poles off the sides of a rubber raft; each pair of sounding locations was determined by the DGPS with a GPS antenna standing in the centre of the raft.

more efficient, and either the region can be divided into several areas accordingly or they can be measured area by area by groups of people. Under the circumstances, the data coverage to the measured topography in the ITZ should be abundant.

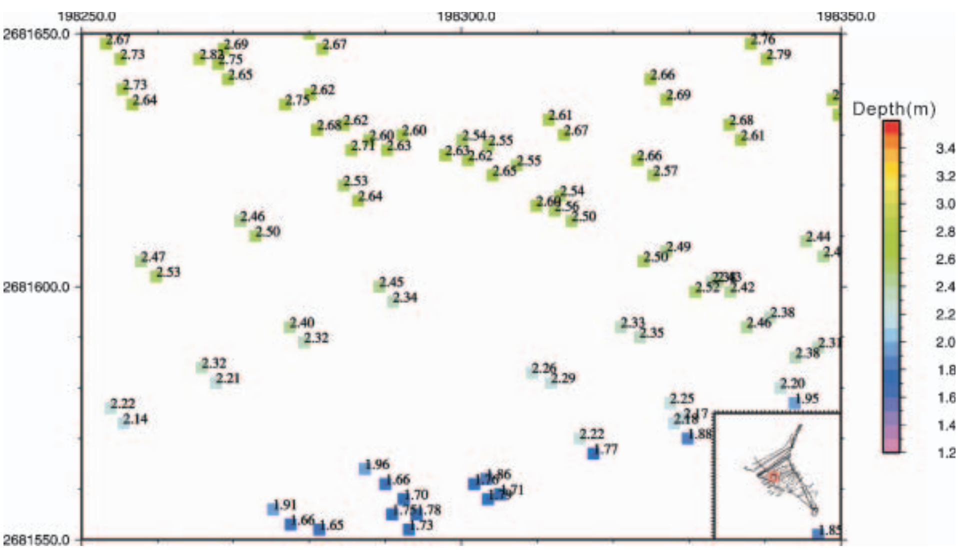

Figure 4. Sweep sounding data distribution in the South Zone. Numbers shown are water depths measured in metres, indicating two soundings as a pair following survey tracks of intervals of 20–25 m.

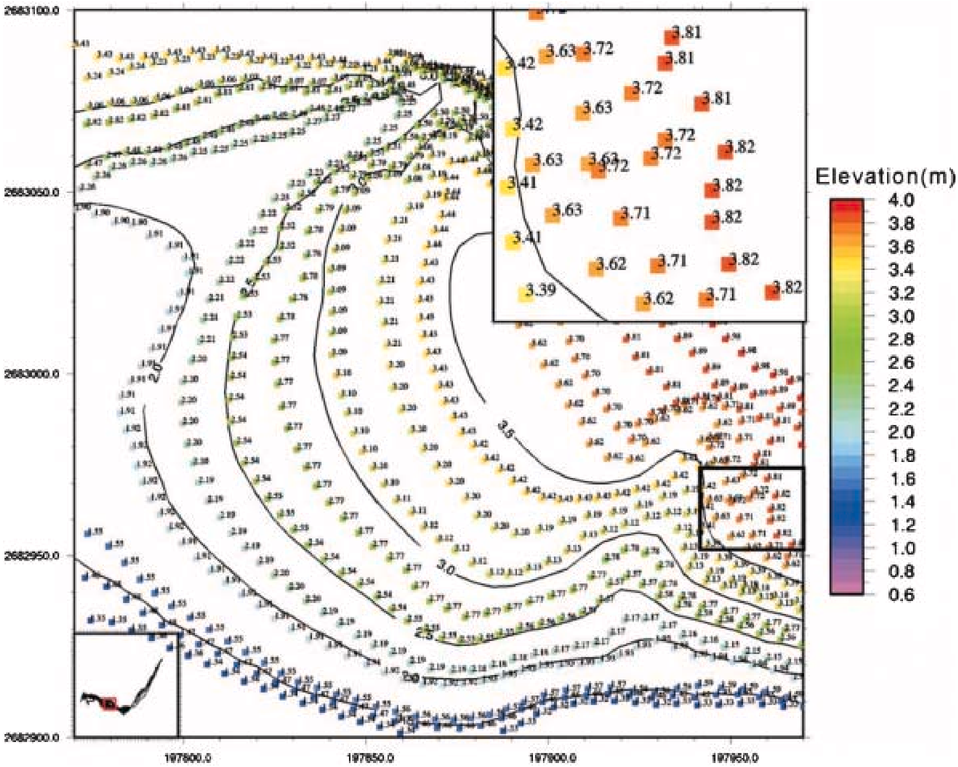

Figure 5. The traces of the backpack tracing lines inside Taichung Harbour. Their locations in the harbour are given in figure 1. The terrain height to each measured location is marked by squares of different colours (with warm colours representing higher altitudes) from 4.0 m to 0.6 m—details are provided in the coloured bar on the right side of the plot. The values of elevation in metres are given in each represented location, alternatively. The graph occupies an area of 200 m × 200 m.

Inside Taichung Harbour, along the water line, there was less energy such that the uprush wave could swash back and forth for a wide distance; therefore, the swash mark defined by the tideline can be clearly located by the backpacker carrying the GPS. Under these conditions, the accuracy of the survey is defined by whether or not the backpacker could follow the trace of the swash zone. However, when the waves were calm, the steeper floor showed a narrower swash zone which could easily be traced by a backpacker. As a result, optimal measurement accuracy can be achieved. However, outside the harbour, for those beaches facing the open sea, defining the tideline trace in the swash zone becomes problematic (figure 6). Waves can be broken and become a series of bores propelling up the beach face. The higher the wave energy or the lower the gradient of the beach face, the wider the swash zone is, and the more difficult it is to recognize the tideline trace.

Figure 7 shows consecutive pictures taken while the waves were propelled up the beach face. It is indicated how the swash zone, which represents a zone with maximum penetration of a shallow wave, was identified when the wave motion was lost by inertia in its forward motion. By knowing how wide this zone was, the accuracy of the measurement can be estimated, according to the calculated gradient in that area. For instance, the beach face gradient (Φ) shown in figure 5 was at about

Figure 6. An assistant carrying a handheld GPS walking through the swash/tideline zone in the Pali near-shore area in 2005. The width of the swash zone is marked on the figures at about 5 m.

1.5° and became 3.0° to the east (estimated from the horizontal spatial separation between the contour lines of 1.5 m and 3 m); the error difference, which is equal to $\tan(\Phi) \times w$, can range from 13 cm to 26 cm for the swash zone width at 5 m (or swash distance at w metres) (figure 8).

Figure 7. Six consecutive images showing the swell approaching the beach, indicating that the swash zone was occupied. The sequence is from right-top corner to left-lower corner. The last picture shows the beginning of another cycle of approaching.

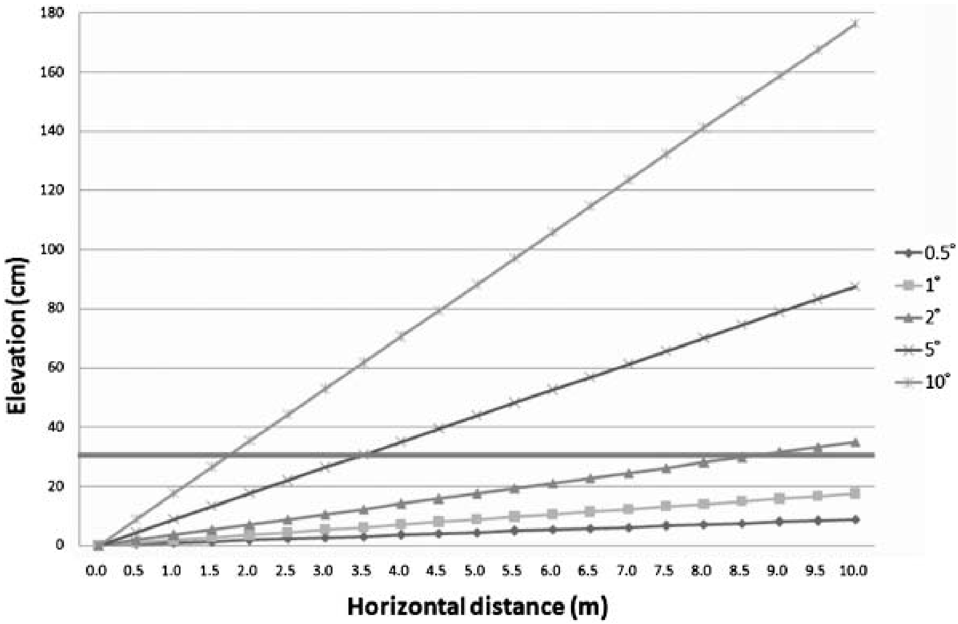

Figure 8. Measured error (in centimetres) versus the swath distance (in metres) in the tideline zone at each varied beach gradient at 0.5, 1, 2, 5 and 10°. The minimum requirement of sounding error in shallow water (<30 m) is 30 cm in the IHO regulation. This threshold is marked with the light grey bold line.

For the tidal zone terrace, which shows a gentle gradient on the bottom, its gradient has been as low as 0.5° (Pethick 1984). As shown in figure 8, a swash zone widens to 10 m in this area, and the tideline tracing method at this gradient gives an error measurement of only 9 cm. Unlike the error obtained by an echo-sounder in the shore zone, this error is within the acceptable error margin of 30 cm as ruled by the International Hydrographic Organization (IHO). If we set a stricter threshold with the allowable margin of error at 10 cm, the width of swash zone for a person to walk on should be no wider than 0.5 m, 1 m, 3 m, 6 m and 11 m, when the gradient is at 10°, 5°, 2°, 1° and 0.5°, respectively. Inside Taichung Harbour, where the swash zone is usually less than 0.5 m wide, given a beach face gradient of less than 1/6 (10°), a contour map with a contour interval of 0.1 m can be produced.

Figures 9 and 10 show the contour plots made by the tideline tracing method and demonstrate the efficiency of the data used in producing the topography in the ITZ zone. The method sampled denser data points distributed on the slope, such that the seaward edge of the beach beam can easily be recognized on the plot. For instance, as shown in the contour plot of figure 9, the boundaries of the low tide terrace were marked, and they all can be seen in the view. In addition, the slopes off the berm and the terrace were all clearly defined with the gradients around 3°–7° by using the tideline tracing dataset.

In Figure 10, the South Zone was truncated by a trench 100–200 m wide, in which the tideline tracing method was no longer applied. A two-beam sweep echo-sounder was thus used to survey during the flood tide period. To complete the contour plot of this area it is necessary to combine the two sets of data (figure 11). Contour lines produced by the echo-sounding measurement exhibited poorer quality than those

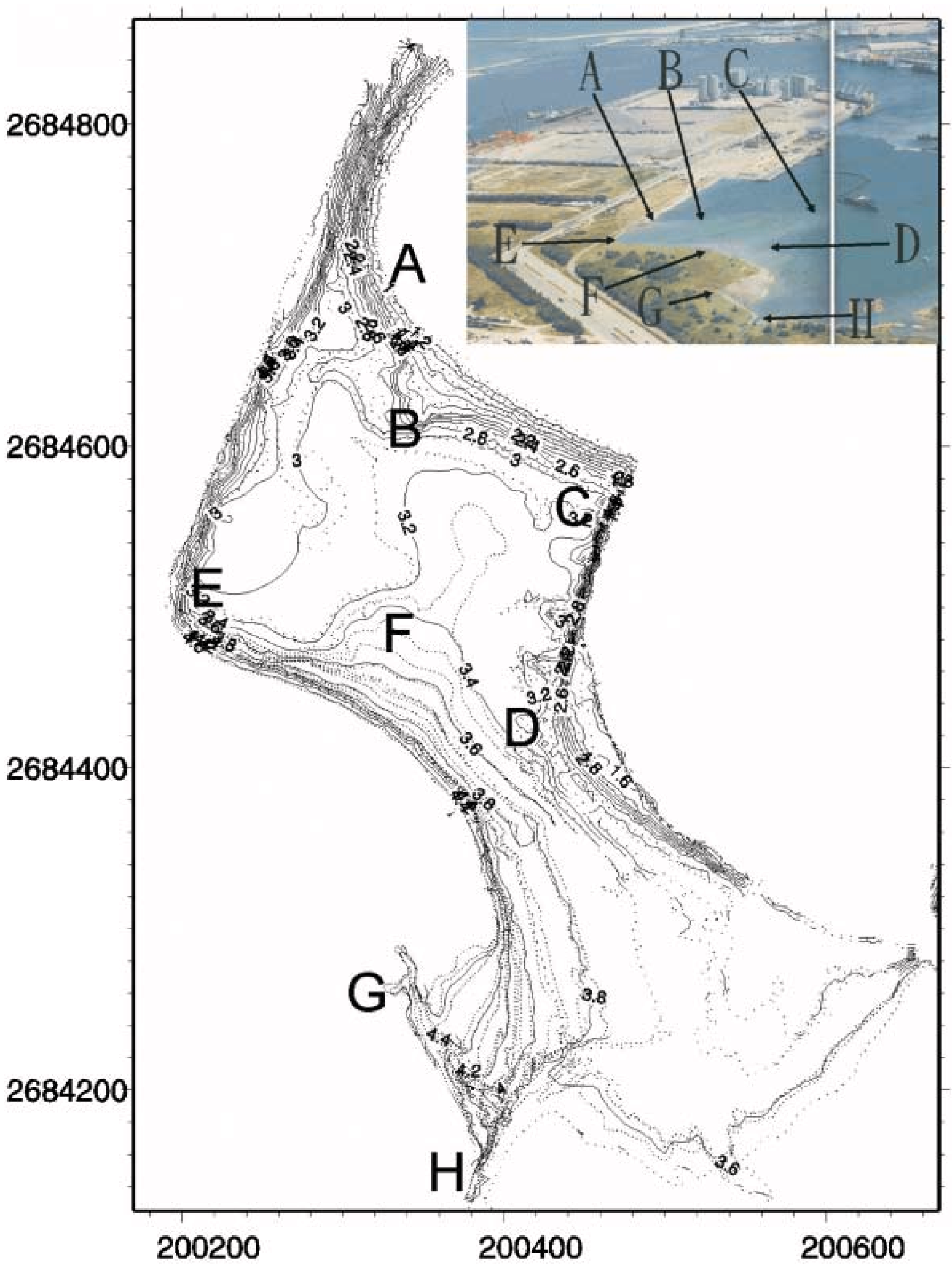

Figure 9. Altitude contours produced in the North Zone. The contour interval is 0.2 m. Lines were obtained by the tideline tracing method. Small dots represent the positions of measurement. The spatial is defined by (E, N) coordinates of the Taiwan Grid, in metres. In the upper right corner, an inset shows an air photograph looking downward to the water in the North Zone before the survey was conducted. The North Zone is located in the right side of water next to the Pier. A submerged low tide terrace (edge denoted by A-B-C-D) in the water, extending from the beach berm (E-F-G-H), can be clearly seen.

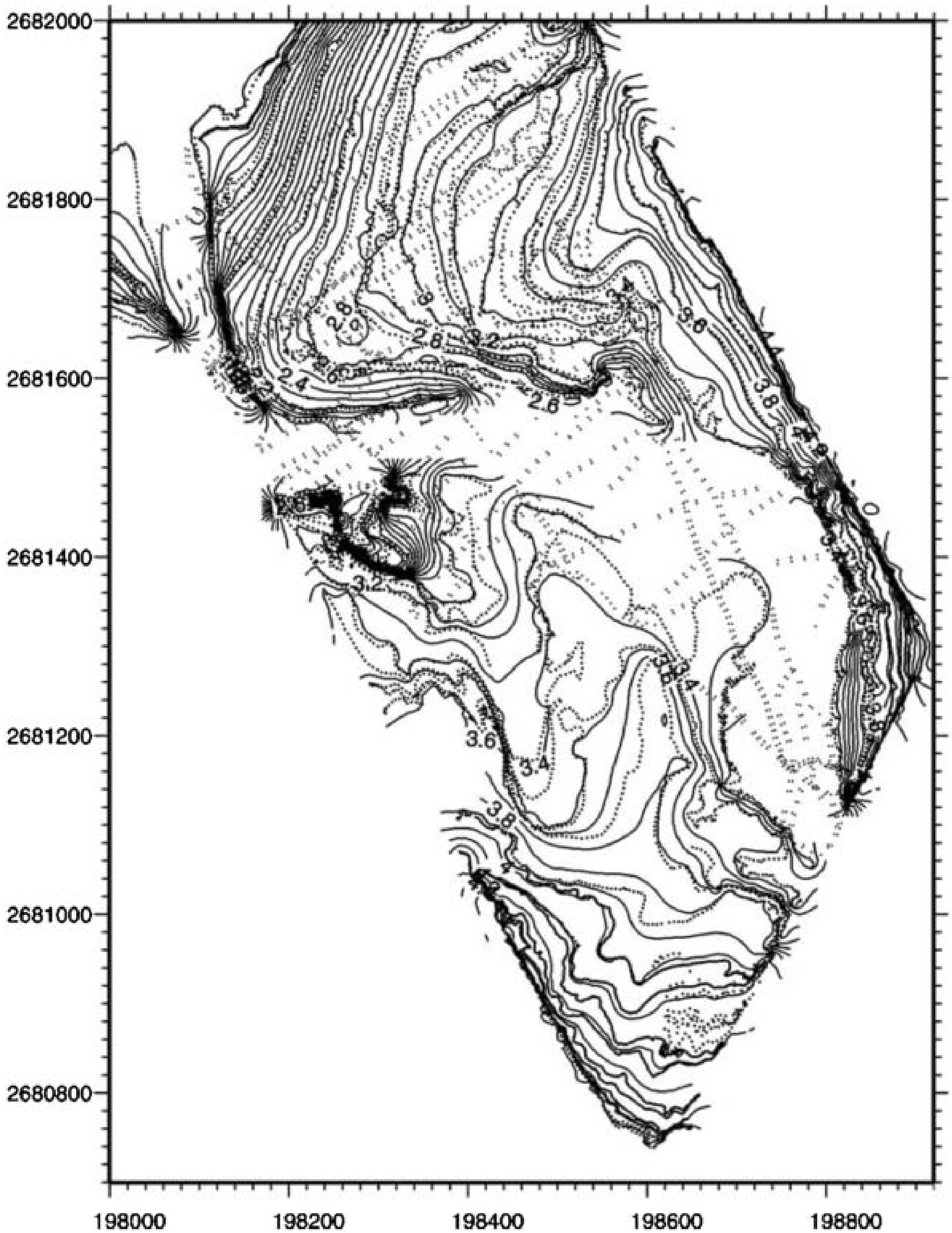

Figure 10. Contours made by the tideline tracing method. Contour interval is at 0.2 m. Between the contour lines are single dots marking the positions measured by the tideline tracing method. Pair dots indicate the points measured using the sweep beam echo sounder method.

obtained by the tideline tracing measurement, with the wavy shape resulting from the numerical gridding. However, except on the bank area of the trench, the difference between these two sets of data was almost within 10 cm, which provides evidence of accuracy within the centimetre scale to the tideline tracing method.

Due to the beam insonification effect of the acoustic wave, an echo-sounder always gives less accuracy of the measurement to a slope bottom (Shiao 1996). This

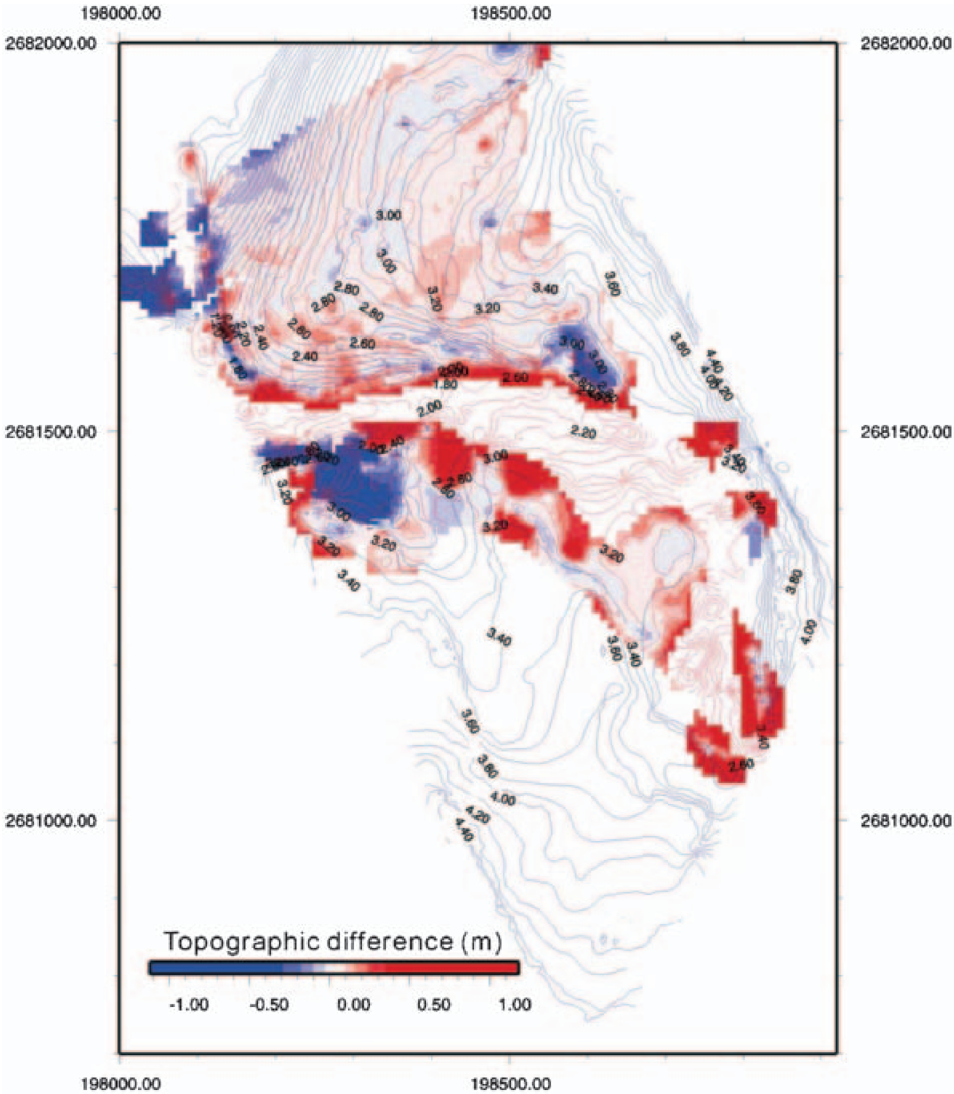

Figure 11. Altitude contours in the South Zone obtained from the soundings and tideline data. The contour interval is 0.1 m. Red contour lines were provided by a sweep's two-beam echo sounder (as in figure 4; its distribution is shown in figure 10), and blue lines by tideline tracing. Value variations of these two methods in the overlapped area are denoted by the coloured bar on the lower left corner.

phenomenon can be seen in figure 11. On the edge of the trench, where the tideline tracing data were available, the comparison varied by at least 20 cm. To ascertain whether or not the variation results from the positioning error occur in-between the datasets, a cross-correlation between the sounding data and the tideline tracing data was made, indicating that two datasets were well correlated without showing significant position error provided by the DGPS (figure 12).

The Central Zone was covered by number of runnels extending from a trench 2 m deep. In addition, an embankment divided the area into the halves, making the topography complicated in this zone. The area, which was sub-aerial, was measured

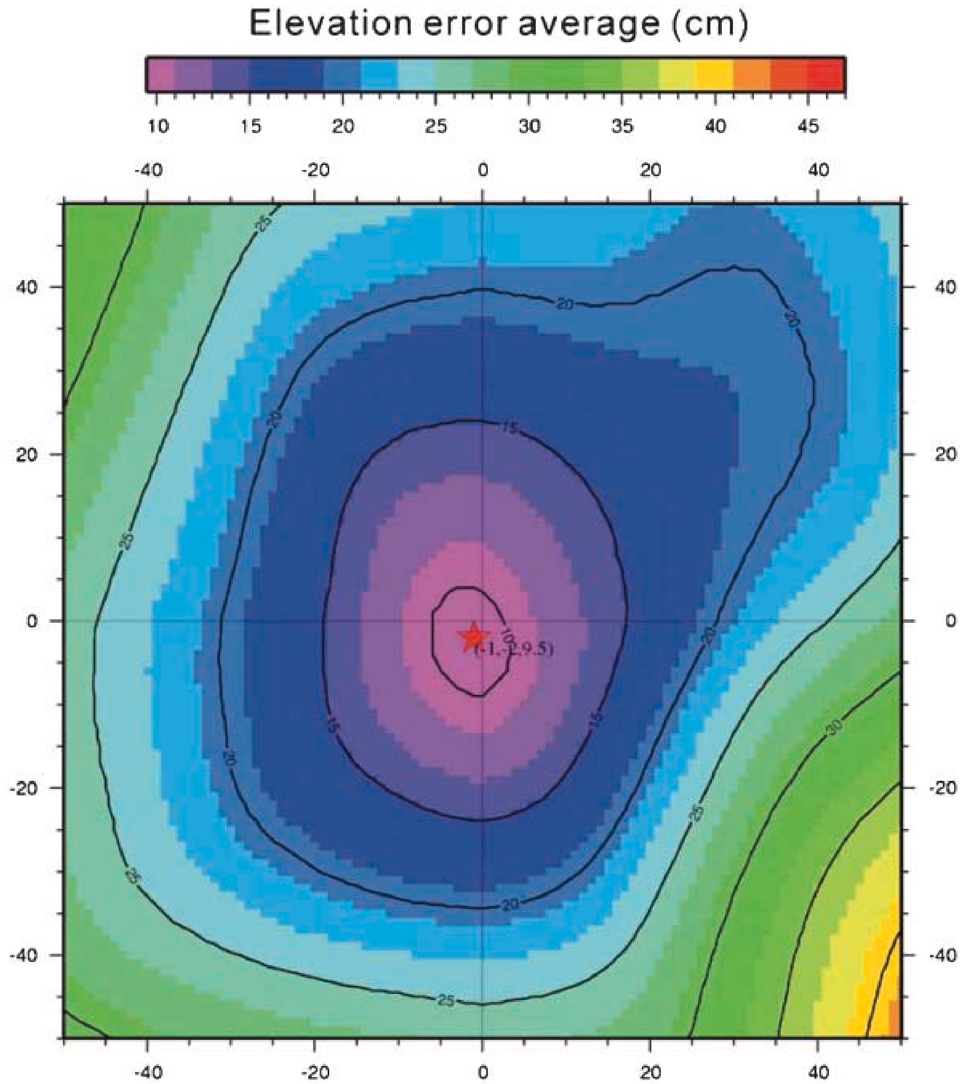

Figure 12. Cross-correlation of sounding data with the tideline tracing data. By shifting the sounding data grid by grid and comparing them with the tracing data in positions, the difference of the sounding and tracing data at each shifted grid point was summed and averaged. Grid points are at intervals of 1 m. The red star indicates the location of the minimal, standing for two datasets being well correlated, as sounding positions being transited south-westward to a (−1 m, −2 m) location.

by the Total Station (figure 13), and the trench, which was submerged at all times, was measured by the echo-sounder. Figure 14 shows the results, indicating detailed topographical features, especially in the littoral zone where surveying was conducted by the tideline tracing method.

3.2. *Pali near-shore area*

A wide variety of troughs and ridges appear in the ITZ near-shore area off the Pali coast. Although the relief of sea level between the flood and neap tide is less than

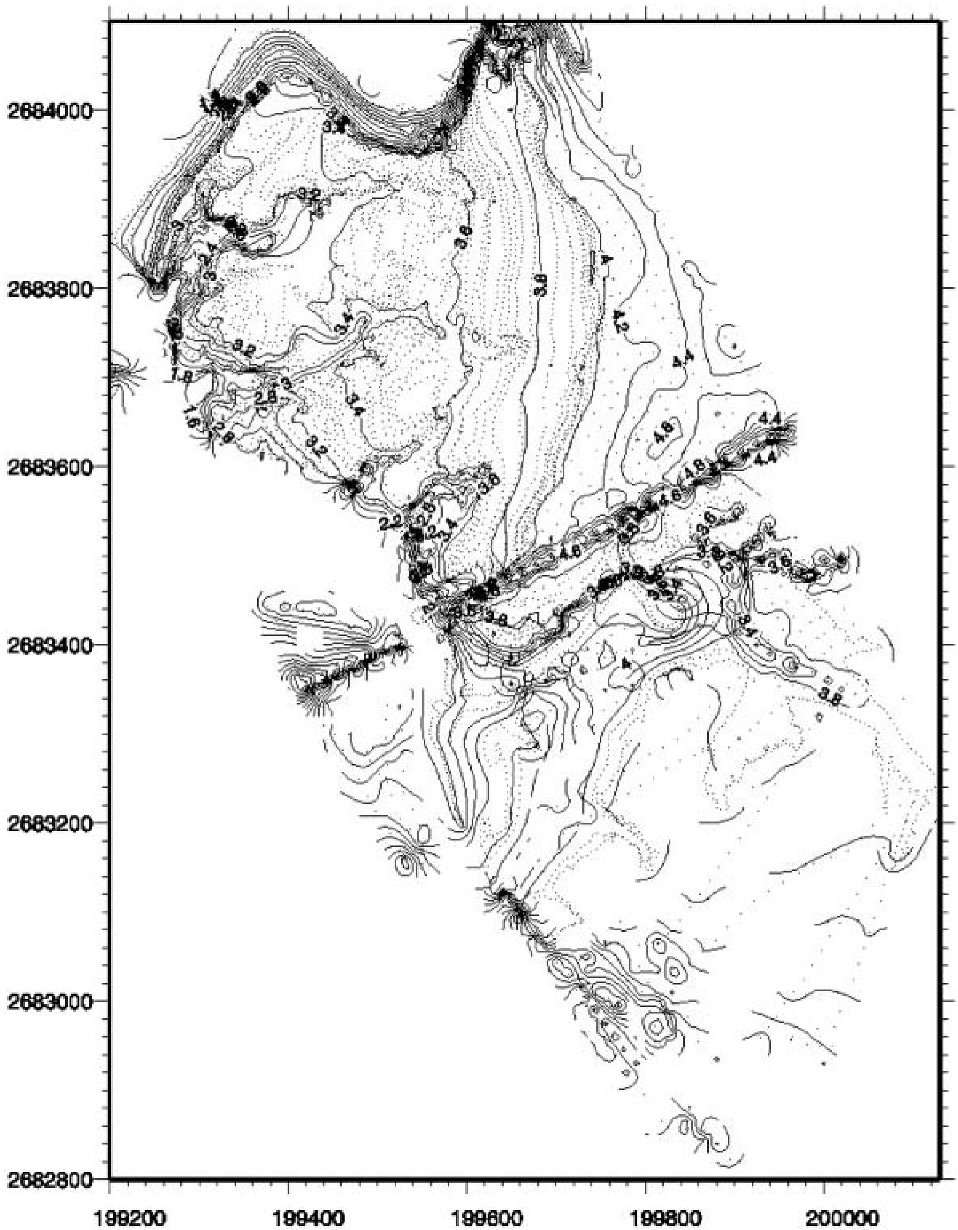

Figure 13. Contours made by the tideline tracing method. Positions measured by tracing tideline are marked by small dots that follow contour lines. Dots truncating with contour lines show the measurements made by the Total Station, mainly indicating the location of a 1.5-m high embankment. Those dots represent the echo sounding measurements, which were mainly located in the trench area of Central Zone.

2 m, the area possesses a wide littoral zone more than 1 km long, making it difficult to map either by echo-sounding or by land surveying. By the mouth of the Danshui River in particular, sediment outputs have produced a wide flat low tide terrace crossed by shore-parallel ridges and runnels (figure 15).

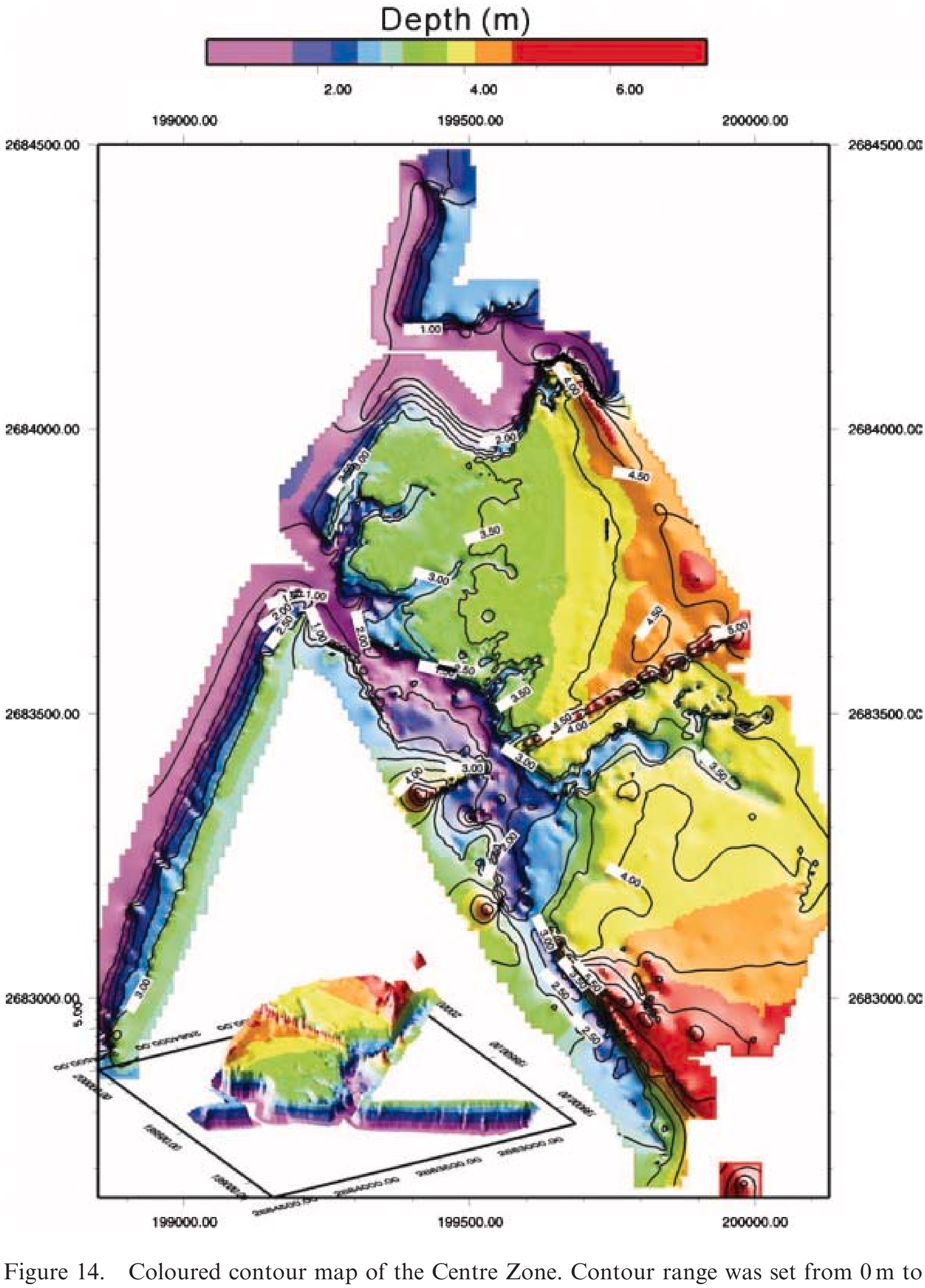

Figure 14. Coloured contour map of the Centre Zone. Contour range was set from 0 m to 7 m with a defined colour bar. This map produces illuminated shadows and some runnels in the area furnished by the measurement, indicating high resolution of the tracing data. The inset in the lower left corner is a 3D topographical draw viewed from the north-west. The map was made using GMT software (Wessel and Smith 1998).

When the longshore barriers are situated in the littoral zone, isolated highs or lows away from the shore line are shown, as seen in figure 15. This feature affects the tideline tracing method and requires the use of two procedures. First, the boundaries

Figure 15. Near-shore off the Pali, a submerged long-shore bar was exposed while the sea retreated; and a runnel then appeared in-between the shore land.

of these barriers must be traced by the tideline tracing method, even if the measurements are as small as the figures in figure 16. Secondly, the area must be surveyed with several beach profiles using RTK when the littoral zone is sub-aerial.

Figure 16 shows the trend of tideline tracing data distributed in the Pali coast. The data are shown to be well matched with the altitude measurements obtained by RTK. Off the shoreline, the low tide terrace is extended from 2 m elevation downslope in an average gradient of 1/300 (0.2°). On the terrace the measurements were sparse, due to a series of sand barriers being exposed individually, so the backpacker needed to cross the runnel from the shore to make a quick survey.

The RTK data define where the barrier or runnels were located in between the sequential tideline measured in the neap tide period. In figure 17, the data obtained by two people in a neap tide period produce a map that shows at least three longshore bars appearing off the coastline in the survey area. The trend and the size of the sand bars are easy to recognize, providing a most efficient and cheap way to measure detailed topography in the ITZ.

4. Conclusions

This paper provides a discussion of an alternative method to the use of echo-sounders in the ITZ in the high tide period, or the use of a laser or GPS in the low tide period. The results of these traditional survey methods may be inaccurate as well as laborious ways of mapping the topography. Considering the coverage of data distribution and the fulfilment of a centimetre scale of topography, the

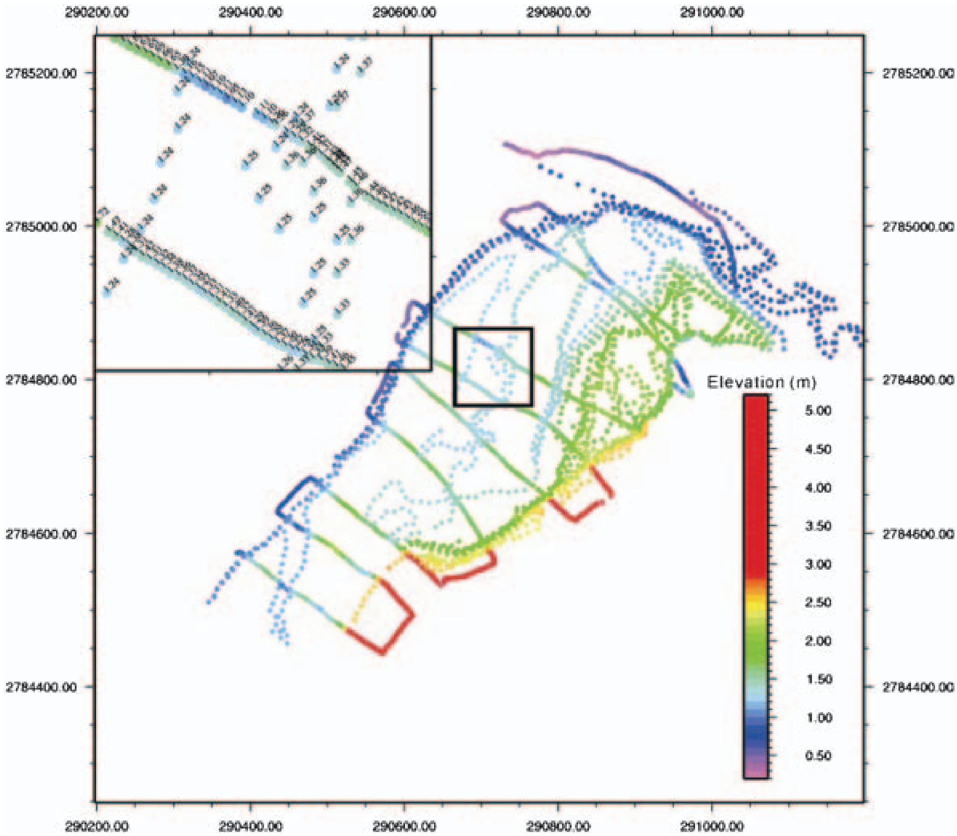

Figure 16. The traces of the backpack tracing lines near-shore off the Pali coast. Terrain height to each dot was marked by different colours (with warm colours representing higher altitudes) from 0.2 m to 5.2 m (details in the coloured bar on the right-lower side of the plot). The graph occupies an area of 1000 m × 1000 m. In addition, the value of elevation of each dot is shown respectively on the upper left zoom in window (100 m × 100 m), which is denoted with a square block on the main plot and elevation ranging from 1.0 m to 1.8 m; the tideline tracing data is distributed parallel to coastline, and the RTK data points are those truncated to the tideline tracing data.

backpack tideline tracing method provides a friendlier, cheaper method. Results indicate its powerful capability to map the littoral topography. The method can also be applied when the low tide terrace is distributed with barriers and runnels, in which the data have to be combined with the results of an RTK survey.

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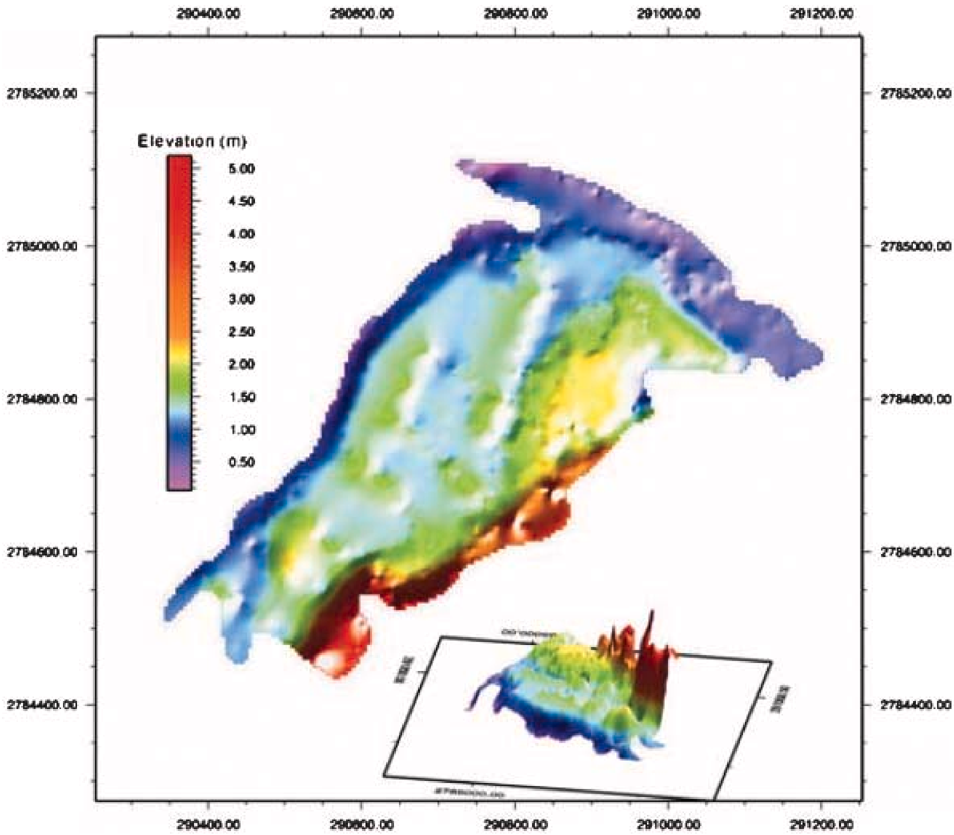

Figure 17. Topographic plot in the region shown in figure 16 denoting the ridges and runnels in the littoral zone shown in figure 16. A 3D plot is presented in right-lower corner and the projection at azimuth is 260°/dipping 25°. Danshui River is located in the north-east corner trended north-west in this area.

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