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Light Detection and Ranging (LiDAR) for Measurement of Coastal Processes

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Abstract

An experimental study has been completed to investigate the ability of a low-cost, industrial 2D LiDAR instrument to obtain detailed measurements of time-varying free-surface elevation in both the laboratory and the field. When mounted above the swash zone of a sandy beach, the LiDAR instrument was able to make swash-surface measurements that compared well with concurrent measurements using an array of ultrasonic altimeters which have been shown to provide accurate point measurements. A significant advantage of using LiDAR technology is that a single instrument can be used to make measurements throughout the swash zone at a high spatial resolution O(1cm) that enables small scale O(10cm) flow features to be evaluated and is impractical using alternative point measurement devices. When mounted above a laboratory wave flume, the LiDAR instrument was shown to make measurements of the time-varying free-surface elevation along a section of the wave flume at a spatial resolution O(10cm) with comparable accuracy to an array on conventional capacitance wave probes. Thus using a laser scanner, a single instrument can be utilised to measure the entire wave field allowing detailed evaluation of wave transformation throughout the experimental domain.

Keywords: LiDAR, swash, remote-sensing, free-surface measurements, wave transformation.

1. Introduction

LiDAR (Light Detection And Ranging) is an optical remote-sensing technology which provides accurate survey measurements of surface topography and allows rapid production of digital elevation models. The device uses the time-of-flight of reflected laser light to determine the distance to multiple points on either a single profile or a 3D surface. LiDAR technology was developed in the 1960's but has been used on a consistent basis since the 1980's for applications in a large range of fields including archaeology, hydrology, meteorology, robotics, agriculture and the military.

The use of airborne LiDAR in coastal research is a commonly used technique. LiDAR allows the rapid collection of morphology data along large regions of coastline, and has been extensively used to map large-scale sub-aerial coastal morphology and nearshore bathymetry [7]. A recent special issue on the role of LiDAR in Coastal Research and Resource Management [6] discussed the potential for the technique to be used in the investigation of nearshore ecosystems (both submerged and emergent), coastal morphodynamics and hazards due to sea-level rise and storminess.

While LiDAR is commonly used for investigations of coastal geomorphology at large spatial scales, the potential to use LiDAR technology to resolve smaller scale coastal processes is yet to be fully exploited. The ability of a single instrument to measure complete 2D or 3D profiles at high spatial and temporal resolution has obvious advantages for both field and laboratory measurements.

This paper will examine the ability of a single low-cost industrial LiDAR instrument to obtain measurements of swash-surface elevation and cross-shore flow velocity in the field as well as laboratory measurements of time-varying free-surface elevation at multiple locations.

2. Instrumentation and Methodology

2.1 LiDAR Instrumentation

The experimental work described in this paper was undertaken using an LMS200-30106 2D laser measurement system manufactured by SICK [11] as shown in Figure 1. The scanner measures the distance to a target using the time delay between the transmission of an eye-safe pulsed laser beam ($\lambda = 905$ nm) and the detection of the reflected signal. The pulsed laser is deflected by an internal rotating mirror to provide a fan shaped scan of multiple points within the LIDAR's 180º field of view at an angular resolution of between 0.25º and 1.0º. The instrument can be configured with a maximum range of 8 m, 30 m or 80 m, with systematic error increasing with range. During both the laboratory and field experiments described here, a maximum range of 8 m was used and the angular resolution was fixed at 0.5º, thus 361 points within the LIDAR's field of view were scanned at a frequency of 37.5 Hz. The instrument manufacturer's specifications indicate that at a range of 8 m the instrument has a resolution of 1 mm and systematic error of ±15 mm. Physical dimensions of the laser measurement system are 185 mm x 156 mm x 155 mm and it has a weight of 4.5 kg which consequently allows it to be easily handled and deployed.

Figure 1 SICK LMS200-30106 LiDAR instrument.

2.2 Experimental Setup – Field Deployment

A field deployment of the SICK laser scanner and additional instrumentation described below was completed at Narrabeen-Collaroy beach in Sydney. Narrabeen-Collaroy is an east-facing embayment, 18km to the north of the Sydney central business district. The embayment is 3.6 km in length, composed of fine to medium quartz sand ($D_{50} \approx 0.3$ mm) and with a typical nearshore gradient of 0.02. During the deployment reported here, spanning 5 hours over high tide on 27th August, 2009, the significant wave height and peak wave period in deepwater were $H_s = 0.58$ m and T_p=11.0s, as measured by the Sydney Waverider Buoy located approximately 11 km from the coast. These conditions, combined with refraction in shallow water ensured that incident waves approached the beach face ($m = 0.12$) essentially shore-normal and resulted in swashes with typical cross-shore excursions of the order of 5 m with the larger swashes extending to 10 m at the experiment location.

To obtain measurements of swash surface elevation, the LiDAR system was mounted 5 m above the beach face on a braced scaffolding pole which was located 9 m seaward of the high tide run-up limit (Figure 2 and 3). Measurements of swash free-surface elevation were made for a total of 137 minutes around high tide while swash excursions extended past the LiDAR location. The diameter of the laser spot on the target location and the spacing between adjacent measurement locations (angular resolution of 0.5º) increase with horizontal distance from the instrument. With the LIDAR positioned 5 m above the beach face, the measurement spot diameter varied from approximately 30 mm directly below the instrument to 40 mm at a horizontal offset of 5 m [11], while the horizontal spot spacing varied in the range 45 mm to 65 mm over the same distance. The LIDAR instrument was logged using a personal computer located at the top of the dune and sampled at the scan rate of 37.5 Hz. During initial post-processing, the LIDAR output was manually de-spiked and smoothed using a 3-point running average in both the space and time dimensions. To provide verification data against which the swash surface elevation measurement made with the LIDAR measurements could be compared, ten ultrasonic altimeters (Massa M300/95) were mounted at 1 m cross-shore intervals, 1 m above the beach face on a scaffold rig (Figure 3). These instruments were described by Turner *et al.* [12] and have been successfully used to measure both bed and free-surface elevation in the swash zone (e.g. [5], [8], [10], [12]). The measurement spot diameter of these sensors when mounted at a height of 1 m is approximately 280 mm. To avoid interference with the LIDAR measurements, it was necessary to offset the ultrasonic altimeter array by 0.35 m from the LIDAR instrument in the longshore direction. The sensors were sampled at 4 Hz and time-synched to the LIDAR by logging to the same personal computer. Swash flow velocity in both the long and cross-shore directions were obtained using a single Valeport Model 802 electromagnetic current meter (EMCM) located 30 mm above the beach face at $x = 2.93$ m (refer Figure 2).

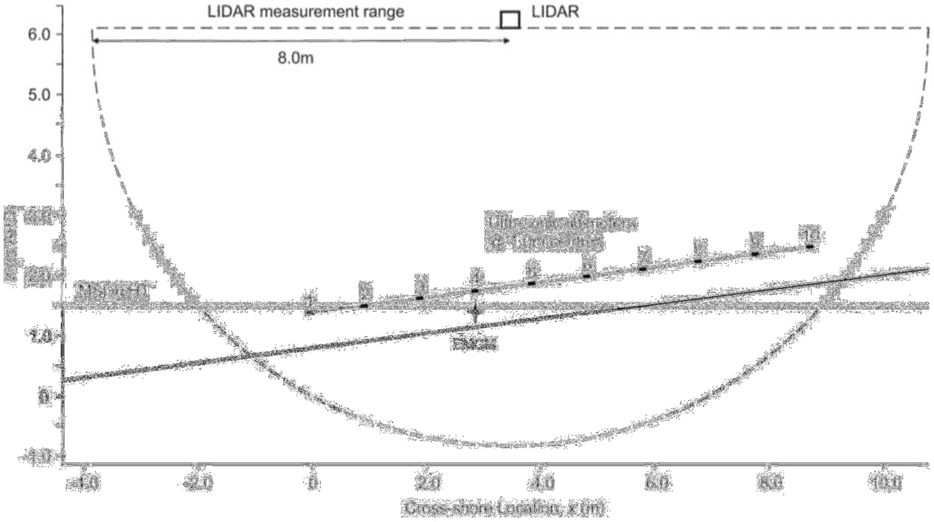

Figure 2 Diagram showing instrument positions during field deployment. The semi-circular region shows the domain scanned by the LiDAR instrument (Figure 2 - Blenkinsopp *et al.*, 2010).

Figure 3 Photograph showing the field instrumentation deployed on a scaffolding rig. The rig was deployed just above MSL at high tide to ensure that swash excursions occurred within the LiDAR field of view.

2.3 Experimental Setup – Laboratory

Laboratory testing of the ability of the SICK laser scanner to measure wave profile was conducted in a two-dimensional wave flume at the University of New South Wales, Water Research Laboratory. The wave flume is equipped with a paddle wavemaker and is 35 m long, 0.9 m in width and filled with water from Manly reservoir to a depth of 1.05 m.

Five different regular wave test cases, with wave frequencies ranging from 1Hz to 2Hz and wave heights from 0.16m to 0.22m were completed to assess the ability of the SICK LiDAR instrument to measure the time-varying wave field in a laboratory wave flume. The LiDAR was installed 3.55 m above the flume bed 6.75 m upstream of the slope crest. The data from the instrument was sampled at a rate of 37.5Hz. To provide additional measurements of time-varying free-surface elevation at fixed points along the flume to verify the performance of the LiDAR, four capacitance wave probes were installed as shown in Figure 4 and sampled at a rate of 120Hz.

A submerged planar slope with a 1:8 gradient and total height of 0.90 m was installed in the base of the flume as shown in Figure 4. This caused waves to shoal as they propagated along the flume and enabled measurements of reshaping waves to be made using the LiDAR.

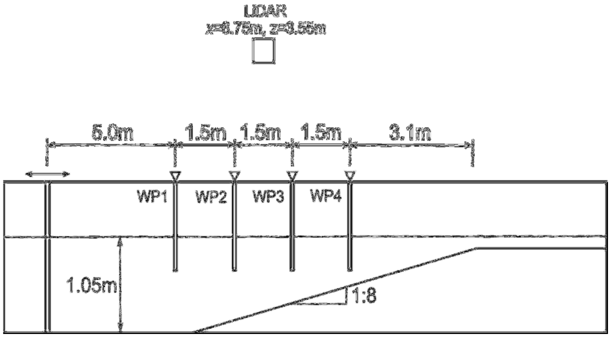

Figure 4 Schematic detailing laboratory apparatus.

2.4 Water Surface Detection

The SICK LMS200 (and similar) instruments were developed as industrial sensors and are commonly used for applications such as collision detection, process automation, determining the position and volumes of objects and the monitoring of open spaces for building security. Detection of water surfaces using a laser measurement system is not a common application, partly because reflections from a smooth water surface are specular and so a return is only achieved when the incident angle of the laser is approximately perpendicular to the surface. Preliminary investigations looking at deepwater ocean waves have found that if small scale perturbations of the free surface are present, scattering and hence the number of returns detected by the LIDAR system are greatly increased and the water surface can be detected more consistently (M. Banner & R. Morison, pers comm.).

In the field, swash flow is typically turbulent and aerated and so the free-surface is roughened by the presence of air bubbles or short waves, particularly during the uprush phase. In small-scale, freshwater laboratory waves however, surface roughness is significantly reduced and entrained air bubbles have significantly reduced residence times [4] meaning that detection of water surfaces is problematic. To overcome this difficulty, a clay mineral, kaolinite was added to the laboratory flumes. This material is neutrally buoyant and provides sufficient seeding to ensure good signal returns from the water surface.

3 Results

3.1 Results - Field Deployment

A comparison of the time-varying free-surface elevation during five typical consecutive swash events relative to Australian Height Datum (AHD) measured at four cross-shore locations (x = 6.90 m, x = 4.93 m, x = 2.93 m, x = 0.99 m) by both the LiDAR and ultrasonic sensors are shown in Figure 5. From Figure 5 it is evident that the data from the two instruments compare favourably.

While the measurements from the LIDAR and ultrasonic sensors show similar variation of swash surface elevation, there are some differences between the two datasets. These are predominantly due to the 0.35 m longshore separation between the ultrasonic altimeter array and the line of sight of the LiDAR which means that the two instruments do not measure exactly the same point in the flow and differences can occur due to 3-dimensional flow effects. Additional discrepancies may be due to the different measurement spot diameters for the LiDAR (30 to 40 mm) and ultrasonic altimeters (280 mm) and the fact that the effective cross-shore location of the individual LIDAR measurement spots moves marginally landward and seaward as the water surface elevation changes. This variation of the laser spot cross-shore position increases with increasing beam angle relative to the vertical and can be removed through suitable post-processing, however for the case illustrated in Figure 5 the

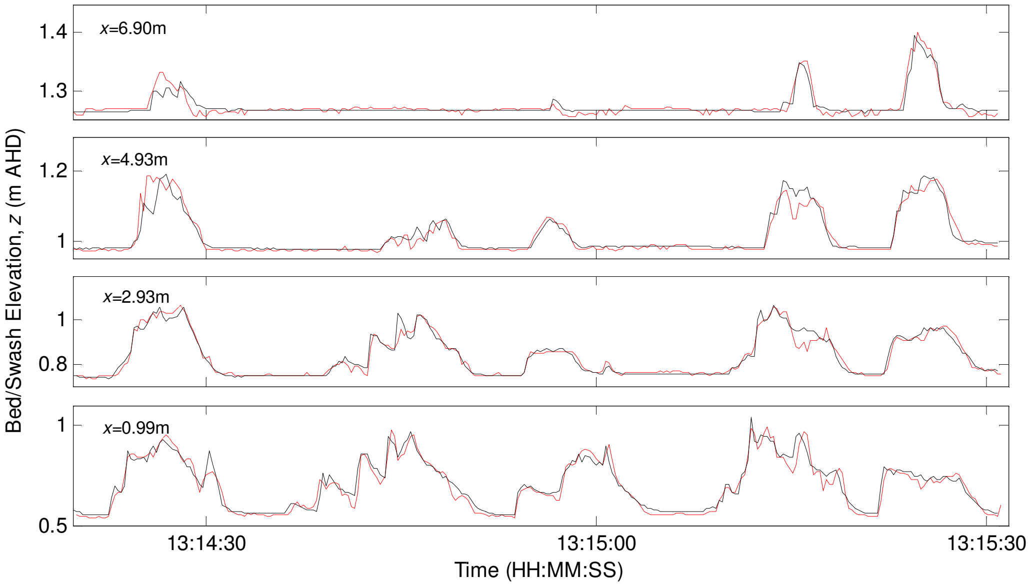

Figure 5 Time-series showing bed/swash elevation measured at four cross-shore locations by both the LiDAR (red) and ultrasonic altimeters (black).

measurement positions moved by up to ±5 mm in the cross-shore. It is noted that in general, the LiDAR measurements appear to be less stable than those from the ultrasonic altimeters, particularly when sighting the stationary ('dry') bed. This is primarily due to additional random noise in the LiDAR output and work is ongoing to improve analysis techniques to identify the source and eliminate this noise.

An assessment of the agreement between the two instruments can be obtained by computing the root mean square difference between the datasets over the course of the full 2 hour sampling period. The RMS differences at the four cross-shore locations examined in Figure 5 were 0.017 m (x = 6.90 m), 0.018 m (x = 4.93 m), 0.028 m (x = 2.93 m) and 0.040 m (x = 0.99 m).

A significant advantage of using a laser scanner to measure swash flows is that a single sensor can be used to obtain multiple and near-synchronous measurements of swash surface elevation with a high spatial resolution O(30 mm). This provides the ability to capture and quantify variations in the slope and elevation of the free-surface which are missed by the ultrasonic altimeter measurements at 1 m spacing. To obtain equivalent measurements using single-point sensors such as pressure transducers, ultrasonic altimeters or capacitance probes would require the deployment of a very extensive sensor array which is expensive, difficult to manage and may significantly interfere with the flow. The higher resolution of the LiDAR measurements in the current experiment is shown Figure 6(a) where the LiDAR data clearly shows the existence of a steep swash front which is erroneously smoothed out by the spatially interpolated ultrasonic measurements. In Figure 6(b) both the LiDAR and ultrasonic altimeter measurements indicate the existence of a swash front, however the interpolated ultrasonic altimeter data significantly underestimates the gradient of this bore. In addition, the LiDAR measurements indicate the existence of a small secondary bore seaward of the swash front.

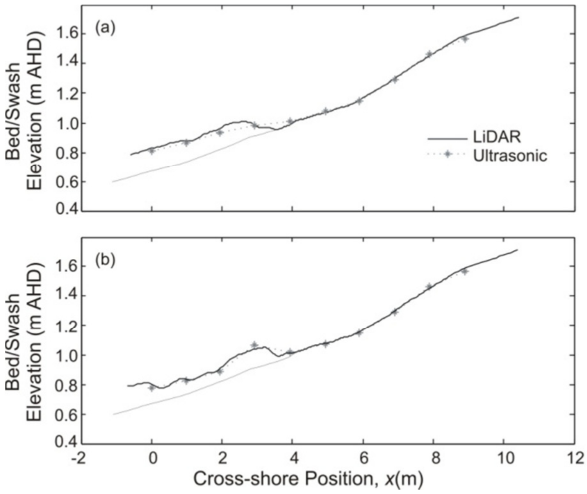

Figure 6 Comparison of high resolution LIDAR data and ultrasonic altimeter measurements at 1 m spacing at two instances in time during an uprush event. The thin black line represents the bed measured by the LIDAR prior to swash uprush. (Source: [3] - Figure 6)

Previous authors [1, 2] have described how swash volume continuity can be used to estimate depth-averaged flow velocity u in the swash zone at any cross-shore location x where time-series measurements of swash volume per unit width landward of the point of interest q and flow depth h are available:

$$u(x,t) = \frac{q(x,t)}{h(x,t)} \qquad (1)$$

The ability to make swash-surface measurements at high spatial resolution using the LiDAR enable depth-averaged cross-shore flow velocity estimates to be made throughout the swash zone from a single instrument. The estimated depth-averaged cross-shore flow velocity during three typical swash events in the mid-swash (x = 2.93 m) is presented in Figure 7 along with concurrent point measurements of flow velocity recorded by a single EMCM at 30 mm above the bed.

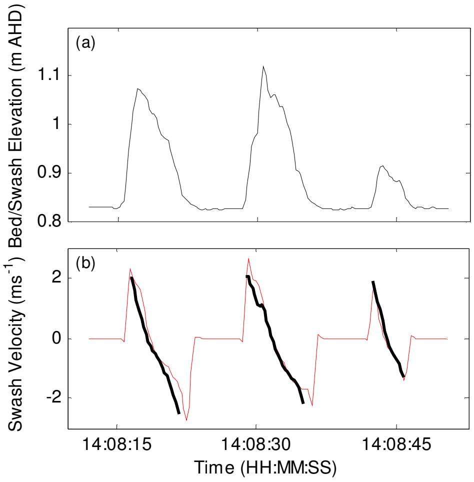

Figure 7 (a) Time-series of bed/swash elevation measured by the LiDAR at *x* = 2.93 m during three swash events. (b) Time-series of cross-shore flow velocity measured using an EMCM (thick black) and estimated using Eq.1 based on the LIDAR data (red). (Source: [3] - Figure 7)

While it is noted that velocity profile in swash flow are not depth-uniform [9], the magnitude and phasing of the individual swash events recorded by both techniques are similar. This supports the conclusion that free-surface measurements from a single LiDAR instrument can be sensibly applied to derive depth-averaged velocity estimates across the swash zone. As noted in [3] and demonstrated in Figure 7, a significant advantage of the continuity based technique is that while some truncation of the velocity record during backwash is inevitable when using fixed current meters mounted a finite distance above the bed, the method described here provides velocity estimates throughout the duration of the swash event.

3.2 Results – Laboratory Experiment

A comparison between the time-varying free-surface measurements made by the LiDAR and the capacitance probe both smoothed using a 3-point running average is presented in Figure 8. It is evident that at wave probe locations 1 to 3, where the wave form is approximately symmetrical, the LiDAR correctly reproduces the free-surface variation measured using the conventional capacitance wave probes. At the location of wave probe 4 where the wave is approaching breaking the LiDAR signal drops out as the steep front face of the wave passes. This occurs because at the location of probe 4, the angle between the LiDAR beam and the SWL is 41º and the front face of the wave is obscured by the wave crest.

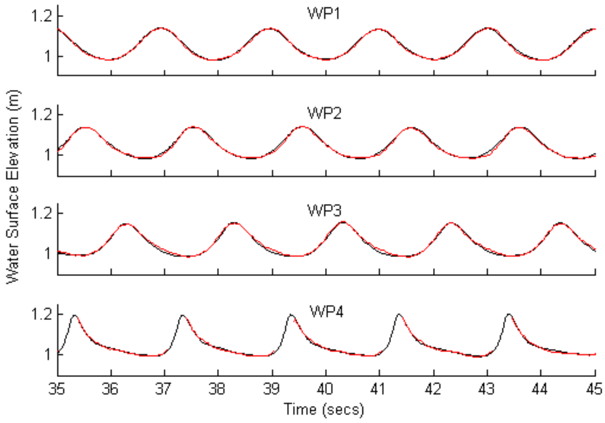

Figure 8 Time-series showing free-surface elevation measured at four cross-shore locations by both the LiDAR (red) and capacitance wave probes (black) during a ten second period. Note that the wave probe (WP) numbers refer to the positions defined in Figure 4.

The ability of the LiDAR to measure time-series of wave profile information rather than just point measurements is demonstrated in Figure 9. This figure shows a 6m profile along the length of the wave flume at three different times as the wave propagates along the flume from left to right and becomes asymmetric as it approaches breaking. The high spatial density of the measurements is evident in Figure 9, with the spatial resolution in the laboratory in the range 15 to 55 mm.

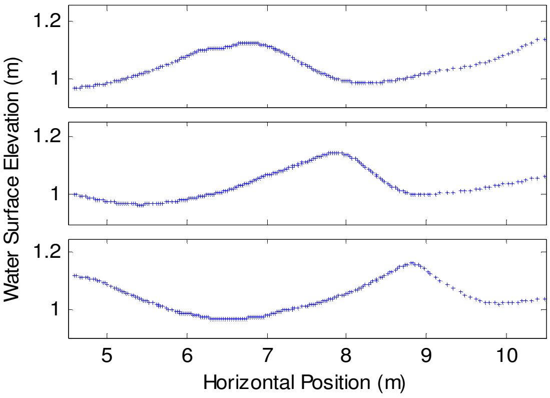

Figure 9 Wave field measured by the LiDAR at three times, separated by 0.5 seconds during the passage of a single wave. Note that each cross represents a single measurement, the high spatial density of the measurements obscures many of the individual points at the scale of this plot.

4. Discussion and Conclusion

This paper has demonstrated the application of low-cost, industrial LiDAR technology for the measurement of free-surface flows in the laboratory and field.

For field applications, the LiDAR instrument is able to obtain measurements of time-varying swash surface elevation with comparable accuracy to an array of ultrasonic altimeters without intruding into the flow. A particular advantage of using the LiDAR is that a single instrument is able to make measurements at a high spatial resolution (O(cm)) that is practically unattainable using alternative techniques. Thus the LiDAR enables relatively small scale flow features to be measured. It has also been demonstrated that by applying swash volume continuity it is possible to obtain estimates of depth-averaged cross-shore flow velocity at multiple points through the swash zone that compare well with the measurements from a fixed current meter. The ability for a single instrument to obtain measurements of swash surface elevation and depth-averaged cross-shore flow velocity at high spatial and temporal resolution throughout the swash zone, potentially replacing large arrays of alternative devices makes it an ideal field research instrument. At present the measurements of bed elevation obtained by the instrument are unsatisfactory and further investigation into this topic is ongoing.

In the laboratory, a single LiDAR instrument was able to make free-surface measurements at O(1cm) spatial resolution along a six metre section of the two-dimensional wave field in a wave flume (Note that longer profiles can be obtained by increasing the height of the LiDAR instrument). The free-surface obtained by the instrument compared favourably with those from four fixed wave probes. It is clear therefore that for applications where detailed measurements of wave profile are required, for example detailed studies of wave transformation, one or more LiDAR instruments could be used to replace large arrays of conventional wave probes and provide significantly higher levels of detail.

The results presented in this paper suggest that a fixed, low-cost, industrial LiDAR instrument can provide free-surface measurements to a level of detail that was previously unattainable and thus represents a profoundly useful tool for the research of coastal processes. In addition it is likely that with further work, LiDAR technology could be used in many other fields of coastal research including measurement of changing bed-elevation in the swash zone, monitoring of the deformation of rubble mound structures in the laboratory and field and detailed measurements of wave transformation in the surf zone of natural beaches.

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