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ABSTRACT

This article describes the active MASW survey conducted at the Jia Bharali River Bed, Tezpur Assam, to identify the shear-wave velocity profile of the subsurface at the site. A new 4-lane (approximately 1.2 km) carriageway bridge construction is proposed over River Jia Bharali, a tributary of River Brahmaputra, intending to connect two national highways NH-52A and NH-37. The site consists of sand and silt deposits, intermingled with pebbles, gravels and perched hard strata formations. The proposed bridge consists of 24 piers and 2 abutments; each separated by an interval of 48 m. Active MASW survey is conducted at the pier and abutment locations, along with roll along mode in between the piers. Multiple sledgehammer shots were used at each location and ‘dispersion image stacking’ is used to generate higher resolution dispersion images. Automated extraction of dispersion curve was attained with the aid of image processing techniques employing an integration of Surfseis and Matlab software packages. The 1-D shear stiffness profile was determined at each of the test location, which is further used to decipher the 2-D shear-wave velocity profile along the bridge alignment. The outcome of the analysis could clearly identify the perched hard strata that prevented the progress of borehole driving at specific locations in the site. The bearing stratum could be properly located which would serve as the foundation depth for the well foundations. The thicknesses of the top erodible sediment deposit, the intermediate soft soil stratum, and the deep-seated bedrock were also effectively recognized. The findings of the survey would aid in effective bridge foundation planning for construction and design.

Keywords: Active MASW survey; Dispersion curve; Automated extraction; Dispersion image stacking; Roll along survey; 2-D shear-wave velocity profile.
INTRODUCTION
Multichannel analysis of surface waves (MASW) is a popularly adopted non-destructive geophysical method used to determine the stiffness of the subsurface stratigraphy. MASW relies on a principle of dispersion of surface/Rayleigh waves generated by a seismic source, where each of the frequency components of the wave travel with a different phase velocity. The dispersion image or, more precisely, the dispersion curve, represents the variation of Rayleigh wave phase velocity with the propagating frequencies. Based on the number of locally predominant phase velocities possessed by a single frequency, the dispersion characteristics are classified as ‘unimodal’ or ‘multimodal’. The fundamental mode (also referred as the M0 dispersion band) represents the combinations of phase velocities and frequencies that carry the highest and the predominant significant energy of the propagating surface waves. The dispersion curve pertaining to the fundamental mode is used in ‘inversion analysis’ to identify the best possible variation of shear-wave velocity with the depth. In recent years, MASW has found its application in different vistas of geotechnical and geophysical survey and investigations. Active MASW survey was successfully applied to map the bedrock in Olathe, Kansas, U.S., ranging over a depth of 1.8-7 m. The potential fracture zones within the bedrock profile were also identified (Miller et al. 1999). Active MASW survey was conducted on the unconsolidated sediments at Fraser River delta, Canada. The shear-wave velocity profile obtained from MASW surveys were found to be within a variation of 15% as compared to the same obtained from actual seismic borehole surveys (Xia et al. 2000a). Active MASW survey is also used for seismic pavement testing (Ryden et al. 2004). In the Indian subcontinent, the shallow subsurface layers of Jabalpur city were effectively mapped using active MASW survey (Seshunarayan and Sundararajan 2004). The same methodology is also used to determine the soil liquefaction potential in Yuan Lin, Taiwan, which were found to favorably match with the same obtained using SCPT shear-wave measurements (Lin et al. 2004). Underwater active MASW surveys (shallow surveys in the range of 1-6 m depth, and deep surveys in the range of 70-130 m depth) are also carried out at Fraser riverbed to evaluate stiffness of bed sediments at Fraser River, Vancouver, Canada (Park et al. 2005). Active MASW surveys are adopted in varying geological and geotechnical terrains including tidal flats in Japan (Watabe and Sassa 2008), compacted ground at Perinth Lake in Sydney (Tokeshi et al. 2013), as well as the failed road sections along LASU-IBA expressway in Alimosho local government area, Lagos, Nigeria (Ayolabi and Adegbola 2014). Active MASW method is also used for the measurement of uncertainty in seismic ground response analysis (Jakka et al. 2014). The existing literatures
highlight the successful application of MASW in varied geotechnical problems. This article presents the successful application of Active MASW survey conducted along Jia Bharali river bed (a tributary of River Brahmaputra) for the proposed construction work of a 1.2 km long bridge along the new 4-lane road from Dolabari to Jamugurihat connecting NH-37A with NH-52 in Tezpur, Assam. By far, this is the longest stretch of geophysical survey conducted on the riverbed in India.

Figure 1 illustrates the location of the mentioned site. The proposed bridge is supposed to consist of 25 spans, and resting on 24 numbers of piers and two abutments (Fig. 2). All the piers and abutments have been planned to support on well foundation.

Fig. 1. Location of Jia Bharali River bed site for the proposed bridge (Source: Google Map)

Fig. 2. Alignment profile of the proposed bridge showing the locations of abutments and piers
Borehole stratigraphy tests were conducted along the alignment of the bridge in few selected locations. While conducting the field SPT tests, at some specific pier locations, the boring had to be stopped within a depth of 15-20 m owing to the presence of a very hard stratum comprising gravel and boulder formations. On the contrary, at some nearby pier locations, the boring easily continued to larger depths (approximately up to 35 m) without any hindrances. It was understood that the hard boulder layers were not omnipresent along the bridge alignment. As the well foundations were planned for all the piers and abutments, it was imperative to identify properly the subsurface stratification. This, in turn, would aid in efficient geotechnical design of the foundations in terms of their settlement, bearing capacity, tilt and shift. Hence, active MASW survey work was conducted for identifying the subsurface stratification and stiffness characteristics along the alignment of the bridge. One-dimensional (1D) spot tests were conducted at all the pier and abutment locations, as well as at the centers of each span. In such 1D spot active MASW surveys, a linear array of geophone receivers (where all the geophone receivers are collinear) is laid in line with an offset to the striking hammer that is considered as the source. The signals collected by the receiver array are analyzed to obtain the shear-wave velocity profile. The estimated profile is considered applicable at the center of the array, and is considered laterally uniform (Park et al. 1999). Two-dimensional (2D) roll-along surveys were also conducted to prepare a spatially distributed subsurface shear-wave velocity profile map. A roll-along dataset has multiple seismic records with same source offset, inter-receiver spacing and receiver array length. The roll-along dataset is prepared through the recompilation of several datasets obtained from several 1D spot surveys conducted collinear to the layout of the receiver array, along a preset survey line. In this case, after each 1D spot survey at a specific location, the receiver array and the active source is shifted along the length of the array, while maintaining a specific overlap between successive layouts. In general, any overlap less than half of the array length is recommended, while the actual overlap is to be determined as per the field conditions and the desired depth of investigation. The profiles obtained from 1D spot surveys are combined with bilinear interpolation scheme to generate a 2-D velocity $(V_s)$ grid-data set, which is further used to construct a 2-D cross section where velocities are usually represented with different color codes (Park et al. 2007). Based on the recommendations of conducting efficient active MASW surveys that generate high-resolution dispersion images (Park et al. 2007; Taipodia et al. 2017, 2018a, 2018b, 2018c), the site investigation was conducted accordingly. The results obtained from the MASW survey have
shown considerable agreement with the limited number of shallow depth borehole profiles available at the said site.

ACTIVE MASW SURVEY AT THE JIA BHARALI RIVERBED SITE

As per the preliminary designs, the proposed bridge would comprise 24 piers and 1 abutment on either side of the riverbank support the bridge. The intermediate spans of the proposed bridge is approximately 48 m. Active MASW tests were conducted at the locations of Abutment A1, P5-P24 and Abutment A2. The locations of the piers P1-P4 were submerged during the period of the test, and hence, the MASW survey could not be conducted at those locations. Among the piers, P16 was located on an inhabited riverbed island comprising moderate vegetation.

The MASW tests were carried out in an active mode using a 10 kg sledgehammer impact as seismic source. The corresponding surface wave signals were recorded by a series of 4.5 Hz geophones arranged in a linear array, wherein all the geophone receivers are placed in a straight line (a standard practice in active MASW survey). The test was conducted using 24-channel array \((N=24)\) with 1 m receiver spacing \((S=1\ m)\) and 4 m offset distance (source to first geophone, \(O=4\ m\)) from abutment A1 to pier P11. Further tests (from pier P12 to abutment A2) were carried out using 12 channel arrays with 2 m receiver spacing, maintaining a constant offset distance as 4 m. The receiver-layout configurations used in the site were selected based on the existing recommendations (Park et al. 2002a; Dikmen et al. 2010; Taipodia et al. 2018c), suitably verified based on trial checks adopted during the field survey. As per existing recommendations (Taipodia et al. 2018c), the sampling time (ratio of number of samples to the sampling frequency) was so chosen that complete propagation of wave energy through the geophone array could be recorded. At each of the test locations, four numbers of sledgehammer impacts (shot gathers) were used to obtain the raw wavefields. As per the existing recommendations (Taipodia et al. 2017 2018a, 2018b, 2018c), dispersion image stacking was adopted to generate high-resolution dispersion image that is capable to provide information about the shear wave velocities of deeper strata. Moreover, active MASW tests were also conducted in a roll-along mode to obtain a 2-D shear-wave velocity profile along the proposed alignment. Figure 3 shows the typical layouts of the geophones and MASW setup in the site, nearby pier locations P6 and P16.
Fig. 3. Typical layout of geophone arrays for Active MASW survey at locations (a) Pier P6 (b) Pier P16

DATA PRE-PROCESSING AND ANALYSIS

The raw wavefields collected from field experimentations were sequentially applied to data pre-processing, dispersion analysis and inversion analysis through Surfseis, a commercial software package. As per the existing recommendations (Taipodia et al. 2018a), the raw data was preprocessed through appropriate filtering and muting of noises in the frequency- and time-domain of collected signals. Band pass filtering in the frequency domain, accompanied by minimal muting in the time domain, was used to preprocess the raw data. The preprocessed data was subjected to dispersion analysis to obtain the dispersion image. A customized image processing code developed in Matlab was used to extract the fundamental mode dispersion curve. The extracted dispersion curve was subjected to inversion analysis. Based on an iterative forward modeling with back feeding of the error in the misfit function (this is a function defining the difference of the experimental and theoretical dispersion curve), the shear wave velocity profile is determined. To
initiate the iteration process, an initial soil model is assumed (also referred as an ‘earth layer model’) comprising 10 layers of varying thickness. Based on the established theoretical formulations (Schwab and Knopoff 1972), the theoretical dispersion curve was extracted for the initial model, and the same was compared to the experimental dispersion curve to calculate the misfit function. Based on the calculated error, the theoretical earth model is updated and subjected to next iteration. After successive number of iterations, the theoretical dispersion curve having the least mismatch (least magnitude of root mean squared error, RMSE) with the experimental dispersion curve was obtained, and the corresponding shear wave velocity ($V_s$) profile is considered the best probable representation of the subsurface stratigraphy.

The accuracy of the dispersion curve extraction depends on the resolution of the dispersion image, which, in turn, is governed by the geometrical layout adopted during the active MASW survey and the signal pre-processing parameters (Taipodia et al. 2017, 2018c). Dispersion image represents the distribution of propagating energy over the comprising phase velocities and frequencies, depicted by successive peaks and ridges. Any dispersion image will be marked by one or more such ridges, illustrating the unimodal or multimodal dispersion of propagating surface waves, wherein waves travelling with a particular frequency can respectively possess a single unique or multiple dominant phase velocities. The extraction of dispersion curve from such an image involves the identification of the localised peak energy band over a range of frequency. The extraction is comparatively accurate for smaller thickness of the energy band, which is illustrated in high-resolution dispersion images (Taipodia et al. 2017). If the energy band is sufficiently narrow, it is possible to decipher the highest energy points from the dispersion image with reasonable precision (Taipodia et al. 2018a). In practice, owing to the adulteration of signal due to various reasons (Taipodia et al. 2018c), obtaining a very thin energy band is not always possible, and accordingly it becomes difficult to decipher the locally highest energy points with significant precision. In this context, to identify the localised highest energy points, a Matlab code is developed by strategically combining image processing and energy filtering subroutines.
DATA ACQUISITION AND DATA PRE-PROCESSING

Influence of Sampling Frequency

Sampling frequency \( (f_s) \) defines the number of samples recorded per second (expressed in ‘sps’) (Proakis and Manolakis 2007). It is a site dependent parameter, which depends on the stiffness of the subsurface soil. Based on the qualitative stiffness of the subsurface material as observed from the limited number of boreholes drilled at the site, as per the available recommendations (Taipodia et al. 2018a), a sampling length of 5120 samples and sampling frequencies of 7500 Hz and 15000 Hz were used to initiate data collection. The above-mentioned two parameters (sampling length and sampling frequency) controls the sampling time. It is intended that during sample collection, the sampling time should be such that the entire packet of propagating wave is completely recorded by the geophone array. At the same time, the sampling time should not be unnecessarily large so that the adulteration from ambient noise in the far geophones can be avoided. For a linear array of 24 geophones at 1 m inter-receiver spacing and 4 m offset distance, Fig. 4 illustrates typical records collected using sampling frequencies of 7500 Hz and 15000 Hz, where both the wavefields exhibit complete recording of the propagating phases. It can be observed that the record collected using sampling frequency 7500 Hz has a higher signal acquisition time. In such case, even after the active signal completely propagates through the receiver array, the geophone continue to record ambient signals that leads to prominent concentration of ambient noise in the record. In comparison to the active signal, the ambient noise possesses comparatively less energy. Thus, prominence of ambient record in a signal reduces the energy content of the recorded signal. Figure 5 depicts the corresponding dispersion images of the typical wavefields exhibited in Fig. 4. It can be noted that although the trend of dispersion are similar, the energy content of the record obtained with sampling frequency 15000 Hz is noticeably more than that obtained with 7500 Hz. Based on these observations, for all the survey locations along the bridge alignment, a sampling frequency of 15000 Hz with a length 5120 samples was chosen. A detailed recommendation about the choice of sampling frequency and time of acquisition for various site conditions can be found in (Taipodia et al. 2018a).
Fig. 4. Typical wavefield records collected at the site comprising 5120 samples and sampling frequency (a) 15000 Hz (b) 7500 Hz ($N=24$, $O=4$ m, $S=1$ m)

Fig. 5. Dispersion images from typical wavefields comprising 5120 samples and sampling frequency (a) 15000 Hz (b) 7500 Hz ($N=24$, $O=4$ m, $S=1$ m)

**Influence of Filtering and Muting**

Filtering is a suitable technique that is used to distinguish and separate the noise from the active signal so that an enhanced resolution of the dispersion image can be obtained (Park et al. 2002b; dal Moro et al. 2003). Based on the existing recommendations (Taipodia et al. 2018a), band-pass filtering was used to efficient removal of noise from active signal, and extract a filtered signal in the range 5-80 Hz, which was found to be effective frequency content of the site. Apart from frequency filtering, ‘muting’ is adopted to remove the low amplitude noises and body wave intrusions from the filtered wavefield. As per the existing recommendations, scanning cone approach is used to achieve optimal muting on the filtered wavefield for the present study (Ivanov
et al. 2005; Taipodia et al. 2018c). Based on the existing guidelines (Taipodia et al. 2018a), a combined application of band-pass filtering and wavefield muting is adopted in the present study. Such combined application is required to obtain dispersion images with best possible resolution and possessing an energy dispersion trend that is distinguishable over a wide frequency band.

Figure 6a shows a typical raw wavefield record obtained from the site, while Figs. 6b, 6c and 6d show the processed wavefields obtained by applying only muting, only filtering and combined filtering-muting processes, respectively. The appreciable improvement of the raw wavefield, when subjected to ‘combined filtering and muting’ technique, can be clearly noticed.

Considering the typical wavefields shown in Fig. 6, the corresponding dispersion images and their qualitative assessment are highlighted in Fig. 7. It can be noticed that the dispersion trend obtained from raw wavefield lacks continuity along the frequency band (Fig. 7a). The dispersion image obtained for the ‘only filtered’ or ‘only muted’ record depicts significant removal of the low frequency content, which is not desirable (Fig. 7b and Fig. 7c, respectively). The dispersion trend obtained from ‘combined filtered and muted record’ highlights a continuous and distinguishable dispersion trend, spanning over a frequency range of 5-20 Hz (Fig. 7d). The obtained dispersion image (Fig. 7d) is of superior resolution than the others, and would aid in the more precise extraction of dispersion curve.
Fig. 6. Typical wavefield records collected at the site and processed using various techniques: (a) Raw wavefield, (b) Wavefield obtained by only muting, (c) Wavefield obtained by only filtering, (d) Wavefield obtained by combined filtering and muting ($f_s=15000$ Hz, $N=5120$, $O=4$ m, $S=1$ m).

Fig. 7. Typical dispersion images corresponding to: (a) Raw wavefield, (b) Wavefield obtained by only muting, (c) Wavefield obtained by only filtering, (d) Wavefield obtained by combined filtering and muting ($f_s=15000$ Hz, $N=5120$, $O=4$ m, $S=1$ m).
Influence of Offset Distance

Offset distance, i.e. the distance of first geophone receiver from the source, plays an important role in obtaining good wavefield records and dispersion images with better resolution (Stokoe II et al. 1994; Park et al. 1999). In case of active surveys, both body and surface waves are generated, while the former is dominant near the striking source owing to the compression waves generated due to the impact. Surface waves, being formed through interference of (P and SV) body waves generated from reflections and refractions, require a certain minimum distance from the source for being dominant. These surface waves are characteristically planar, while the intrusion of body waves or ambient noise wavefields lead to the formation of non-planar waves. It is intended that the receiver array record planar wavefield that are predominantly surface waves, which is possible to obtain after the generated wavefield has travelled a specific distance from its source of generation. This distance beyond which a wavefield exhibits planar wave propagation is termed as the near-offset. Waves with longer wavelengths travel greater distances before they become planar, and otherwise. Further, a very large source-offset distance may lead to the attenuation of the wavefield energy even before reaching the geophone array. The upper limit of such offset distance is termed as far-offset effect, beyond which the geophone array cannot record the impact-generated wavefield. Hence, there are two kinds of prevalent effects which depend on the offset distance, namely the near-offset effects and the far-offset effects, the detailed treatise of which are available in literature (Park et al. 1999, 2002a; Park 2011). The characteristic of both near- and far-offset effect is specific to a site and is dependent on the wavelength content of the wavefield. Based on the existing recommendations (Taipodia et al. 2018c), to check the influence of offset distance on the generated dispersion image, active MASW tests were conducted at pier location P5, by considering two different offset distances of 0 m (the first geophone was right beside the source) and 4 m. Figure 8 shows typical wavfields generated from the two chosen offsets, and the corresponding dispersion images are shown in Fig. 9. It can be observed that the dispersion images obtained for test with 0 m offset exhibits a curtailed M0 dispersion band, with the energy content primarily accumulated at low frequency region, thus exhibiting near-offset effect. The fundamental dispersion band obtained with 4 m offset is found to be more distinct, as well as spanning over a wider frequency band, i.e. approximately 2-25 Hz. Hence, for the present study, all the active MASW tests were conducted with 4 m offset.
Fig. 8. Typical wavefield records collected at pier location P5 using varying offsets (a) 0 m (b) 4 m ($f_s=15000$ Hz, $N=5120$, $S=1$ m, $N=24$)

Fig. 9. Dispersion images from wavefield records collected at pier location P5 using varying offsets (a) 0 m (b) 4 m ($f_s=15000$ Hz, $N=5120$, $S=1$ m, $N=24$)
Fig. 10. Dispersion images obtained from varying numbers of stacks (a) 0 stack, single shot (b) 1 stack, 2 shots (c) 2 stack, 3 shots (d) 3 stack, 4 shots \( (f_s=15000 \text{ Hz}, N=5120, O=4 \text{ m}, S=1 \text{ m}, N=24) \)

**Influence of Stacking**

Dispersion image stacking is a process of generating resultant higher-energy dispersion images by combining the individual dispersion images from repeated shot gathers (Taipodia and Dey 2018). It is conventionally assumed that vertical stacking increases the signal-to-noise ratio (SNR) by the square root of the number of repetitions (Foti et al. 2015). Figure 10 exhibits the influence of stacking of dispersion images considering different repetitions of impacts from the 10 kg sledgehammer. It can be observed that with increasing shot gathers, the distinctness of the dispersion image increases, i.e. the resolution and sharpness of the dispersion trend increases. For the present study, 3 numbers of dispersion image stacks were considered for the complete investigation along the proposed bridge alignment.
Selection and Extraction of Dispersion Curve

Manual Selection

In any other commercial software regularly used for identification of subsurface from MASW records (Surfseis is used in the present study), the fundamental dispersion curve is extracted by manually selecting the dispersion points that are visually recognized to possess highest energy in the dispersion image (as shown in Fig. 11). Figure 11a exhibits the dispersion image where the darkest color represents the maximum concentration of propagating energy over specific combinations of frequency and phase velocities. The white points marked on Fig. 11a are the ones manually selected, as per the user discretion, to represent the dispersion trend. Figure 11b is a snapshot of the details of the selected points highlighting the number of data points selected, and their corresponding frequency, phase velocity and associated SNR. It can be observed that many of the selected points have the SNR value below 0.97, thus indicating a comparatively poor selection of the dispersion points. Such dispersion points are selected on the basis of a misinterpreted peak energy, while in reality the point selected has lesser energy and does not represent the point with peak energy. In this context, the manually selected dispersion curve does not truly represent the fundamental mode. Moreover, the manual selection is based on subjective user discretion and does not have a quantitative basis. In this context, the repeatability of the manual selection of M0 dispersion curve is significantly low, as it is impossible to choose the same dispersion points in each repetition. Thus, such an approach would lead to diverse shear wave velocity profiles based on the repetitions of the manual extraction of dispersion curve, which raises a concern towards the reliability of the post-processing analysis. Hence, it is necessary to develop an automated quantified extraction of the M0 dispersion curve, and the same is described in the next section.
Fig. 1. (a) Typical representation of manual selection of the dispersion curve (b) Screenshot of the data obtained from the manual selection comprising their associated frequency, phase velocity and SNR

Automated Selection

The dispersion image is a three-dimensional plot comprising frequency and phase velocity as the abscissa and ordinate, respectively, while the energy content is represented by colour shadings as the third-dimension entity (as shown in Fig. 11a). In the manual selection, the user attempts to identify the peak energy points based on the colour coding. However, as the colour coding is presented only as legend comprising histogram bins, the selection is purely subjective and, as explained earlier, may not truly identify the peak energy. In this regard, it is necessary to resolve the colour coding in red-green-blue (RGB) and map the same with the distribution of the energy content. This process results in an actual three-dimensional representation of the dispersion image, as typically shown in Fig. 12a. The 3D image is reconstructed from the 2D dispersion image with the aid of a series of image processing subroutines in MatLab. The 3D representation of the dispersion image provides a clearer identification of the peak energies and its trend. Moreover, as the entire image is pixelated, the digitization provides the energy at each possible combination of frequency and phase velocity. Subsequently, the digitized image is subjected to ‘energy peak identifier’ subroutine which identifies the energy peaks that exceed a threshold value (99% normalized energy in the present study; the normalized energy is defined as the ratio of the actual energy to the global maximum energy in the dispersion image space). Figure 12b shows the fundamental mode dispersion curve extracted from the corresponding dispersion image (as shown in Fig. 12a) based on the above-described technique.
Fig. 12. (a) 3D representation of dispersion image obtained from MATLAB based coding related to energy concentrations (b) Identification of the fundamental dispersion curve as the locally highest energy peaks

Figure 13a shows the screenshot of the data obtained through the automated extraction of the dispersion curve. It can be observed that the automated extraction yields significantly more data points (747 points in this case, against 24 points against the manually extracted points). Each of the data-points are attributed with high SNR values, thereby indicating superior quality of the extracted dispersion curve. Moreover, the higher number of points delineated by automated extraction results in increased precision of the extracted dispersion curve. The obtained dispersion curve, in its digitized form, is imported and integrated as the *.txt file in Surfseis, which is subsequently used in the inversion analysis to obtain the shear-wave velocity profile with depth. The adopted technique removes any possible user intervention in the extraction of dispersion curve and thus ensures reliability and absolute repeatability of the obtained shear-wave velocity profile.

Figure 13b exhibits the shear-wave velocity profiles obtained from the dispersion curves extracted using manual and automated techniques. It is observed that the automated extraction approach leads to higher depth of investigation, owing to the precision of the points selected at the lower frequencies, which was not possible to achieve through manual extraction.
Fig. 13. (a) Screenshot of the data obtained from the automated extraction of dispersion curve (b) Shear-wave velocity profiles obtained using dispersion curves extracted through manual and automated techniques

**SHEAR-WAVE VELOCITY PROFILES ALONG THE PROPOSED BRIDGE ALIGNMENT**

Based on the data acquisitions, data pre-processing and the automated extraction technique described in the earlier sections, the shear-wave velocity at all the piers and abutments along the proposed bridge alignment is estimated (Fig. 14). The soils at various depths within the subsurface can be categorized as per the NEHRP soil profile-type classification (BSSC 2004). It is observed that in the locations spanning between Abutment 1 - Pier 7 and Pier 23-Abutment 2, the shear-wave velocity exceeded 300 m/s beyond a depth of 25-30 m, indicating the possible presence of denser and stiffer soils. Some locations exhibited the presence of soft patches of soils in deeper strata (e.g. P9, P17, P18, and P22).
Fig. 14 (a-v). Shear-wave velocity profiles at different abutment and pier locations along the proposed alignment of the bridge over Jia Bharali River.

Figure 15 shows a typical comparative between the $V_s$ profile obtained using MASW test at the location of Pier-18 with the same determined from the standard penetration test (SPT) $N$-values obtained from borehole exploratory data. The SPT-$N$ values were used to calculate $V_s$ by following the relationship proposed by Imai and Tonouchi (1982). The shear-wave velocity profiles are in appreciable agreement with each other, thereby highlighting the efficacy of the automated extraction technique in revealing the subsurface stratification. Moreover, the outcome also suggests that even through the physical borehole exploration technique can yield limited depth information (either due to the presence of hard or stiff subsurface layers or due to restricted of capacity of the exploratory instruments), non-destructive geophysical exploration can be an effective tool in identifying the deep subsurface stratifications. For the typical profile depicted in Fig. 15, it is observed that the borehole exploration could identify up to approximately 20 m depth of subsurface, whereas the MASW approach could suitably identify up to approximately 50 m.
depth of the subsurface. Further, the geophysical investigation could reveal the presence of comparatively softer strata beyond a depth of 20 m, which can possibly produce noticeable influence in the settlement of the proposed foundation, which could not likely be identified by the results of borehole exploration technique.

Fig. 15. Typical comparative of the shear-wave velocity profile obtained using borehole exploration and MASW tests at the location of Pier P18

Apart from the spot surveys at the pier and abutment locations, as per the given recommendations (Xia et al. 2000b; Park 2005), roll-along active MASW survey was conducted between the locations of Pier-5 to Abutment-2. For roll-along surveys, the subsurface profiles are subjected to distortion if the propagating wavelengths are shorter than or comparable to the receiver-spread length adopted in the experiment. The distortion is minimal when the interval of roll-along (i.e. the overlap) is less than 25 times the spacing of the geophone receivers, while being less than the receiver spread length (Park 2005). In the present study, for spread lengths of 48 m and inter-receiver spacing of 1 m or 2 m, a 24 m roll along overlap length was used, thereby conforming to the recommendation for avoiding the distortion in the subsurface profile. The outcome of the survey is provided as the 2-D variation of shear-wave velocity profile along the proposed alignment of the bridge, as exhibited in Fig. 16. For preparing the results of roll along survey, the stacked dispersion images from the spot surveys at each of the abutments and piers (Fig. 14), along
with the intermediate positions between the piers, were used to obtain the 1-D shear-wave velocity profiles. The profiles obtained at each of the spot survey locations were subjected to a bilinear spatial interpolation technique (already incorporated in Surfseis) to obtain the 2-D shear-wave velocity imagery of the riverbed subsurface along the alignment of the bridge.

It can be observed that a layer of extremely low shear-wave velocity exists at the top 5-7 m which is practically the silty and sandy sediment load carried by the river during the monsoon season. The depth of this layer indicates the thickness of the top erodible portion of the riverbed, which should be cautiously avoided to be the founding strata of the bridge pier foundations. It is also observed that at a depth of around 30-35 m from the ground surface, all along the riverbed, a relatively softer patch of soil stratum ($V_s < 200$ m/s, approx.) is sandwiched between sufficiently stiffer strata ($V_s > 600$ m/s, approx.). It is also advised to avoid this particular layer of soil as the bearing stratum of the proposed well foundations. As indicated by the low shear-wave velocities, the layer has low stiffness that might be susceptible to compression or settlement, which can adversely affect the bearing capacity of the foundation. Intermittent existence of hard patches ($V_s > 600$ m/s, approx.) can be observed at depths of 13-25 m. It was reported that driving of boreholes in the riverbed for exploratory purposes could not be carried out uniformly due to the presence of very hard or rocky stratum at scattered locations. At locations of piers P11-P12, borehole drilling could not progress beyond 15 m, due to the damage incurred by the drill bits due to the presence of gravelly or rocky chunks. On the contrary, at locations around pier P20, borehole drilling progressed with relative ease to larger depths of 20-22 m. It can be observed from Fig. 16 that the observations made during the field-testing are in appreciable agreement with the findings of the 2D active MASW roll-along survey. The 2-D profile could well identify the location of the perched patches of hard stratum that would aid in planning the excavation works to be conducted in the site for further borehole investigations. The 2-D profile also clearly identifies the presence of hard strata beyond the depth of 45-50 m all along the riverbed, which can possibly serve as the bearing stratum for the proposed foundations of the bridge piers. This finding would provide a proper benchmark for foundation layout plan and would aid in the foundation design for the river bridge. The presence of very hard strata ($V_s > 1200$ m/s, approx.) beyond a depth of 80-85 m indicates the possible bedrock in the area.
SUMMARY AND CONCLUSIONS

This article presents a descriptive on the Active MASW survey conducted at the Jia Bharali riverbed at Tezpur, Assam. The proposed site for a 1.2 km long bridge, connecting NH37A at Dolabari and NH52 at Jamugurihat, needed to be investigated to determine the subsurface stratigraphy for the purpose of future planning of foundation excavation and design. Both spot 1D survey and 2D roll-along active MASW surveys were conducted at the site. Following the standard recommendations, the sampling time and offset distances were suitably adopted for the site to obtain a best possible record of the propagating wavefields. Combined band-pass filtering and muting was adopted to refine the recorded wavefields for obtaining higher resolution dispersion images. Dispersion image stacking was adopted to stack three shot gathers at each of the test locations, thereby ensuring a continuous dispersion trend spanning over a recognizable frequency band. An automated technique, based on image processing and threshold energy filtering, was adopted to precisely and reliably extract the fundamental mode dispersion curve from the dispersion image. The automated dispersion curve extraction technique removed the user.
subjectivity, thereby producing reliable and repeatable shear-wave velocity profiles, which was not possible with the conventional manual extraction method. Moreover, the automated extraction process significantly improved the SNR of the extracted dispersion curve, even in the low frequency regions, thereby enhancing the depth of investigation of the active survey. The 1D shear-wave velocity profiles were determined at all the proposed and accessible berdge abutments and piers. Following the standard recommendations, 2D roll-along active MASW survey was adopted to identify the continuous profile of shear wave velocity all along the proposed alignment of the bridge. The obtained profile could clearly identify the thickness of the erodible riverbed sediment (at 5-7 m depth from subsurface), locations of the perched hard strata (at variable locations and depths), sandwiched soft layer (at 30-35 m from the subsurface) and the deeper level bedrock (beyond 80-85 m). The findings from the geophysical investigations were in conformity to the limited number of profiles obtained from borehole investigations. Based on the geophysical survey, the soil layer beyond the depths of 45-50 m was identified and proposed as bearing stratum, which would be largely free from the adverse settlement effects of the overlying soft strata, and would prevent any likely distress in the superstructure and the foundation. All these information would provide a basis of planning the foundation layout and design for the proposed bridge project. The strategy adopted in this study can be suitably used in any other simialr studies involving foundation design and planning.

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DISCLOSURES

Data Availability Statement: Some or all data, models, or code generated or used during the study are available from the corresponding author by request. The data comprises volumes of wavefield records collected during the site investigation.

Conflict of Interest: The authors declare that they do not have any conflict of interest

Submission Ethics: The authors declare that all of them mentioned have participated in the site investigation and the preparation of the manuscript. The work submitted herein has not been
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REFERENCES


