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Crustal thickness and velocity structure beneath Singapore's seismic network

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ABSTRACT

We estimated the crustal thickness and velocity structure beneath the five stations comprising the Republic of Singapore's seismic network. Our data set was composed of 697 teleseismic receiver functions and 7 months of broad-band data that was cross-correlated to produce inter-station Green's functions. Surface wave group velocities were extracted from the Green's functions to obtain dispersion data for a path from central Sumatra to Singapore in order to provide a complimentary data set to the receiver functions. Crustal thickness was estimated via an $H - k$ stacking technique, and high-resolution 1D *P*-wave velocity profiles were generated beneath each station by jointly inverting receiver function stacks and the group velocity data using a linearised time-domain inversion scheme. Crustal thickness beneath four stations was found to be between 28.0 km and 32.0 km, while one station in the northeast of Singapore indicates 24.0 km thick crust. This implies a significant crustal thinning beneath Singapore over the lateral extent of 50.0 km. Inversion results exhibit several crustal features that are observable in the derived models at all five stations, indicating that they exist across Singapore as a whole. There appears to be an upper-crustal high-velocity zone beneath Singapore, underlain by a velocity inversion. Station NTU shows slower near-surface velocities than the other stations, consistent with its situation above the sedimentary Jurong formation. These results expand the available global velocity data set, as well as being useful for assessing the seismic hazard in Singapore.

1. Introduction

The Republic of Singapore, a highly-urbanised city-state with a population of 5.2 million, is located at the southern tip of the Malay peninsula. The nation occupies 63 islands with a combined area of roughly 700.0 square kilometres, of which some 77% contains significant built infrastructure. The seismic hazard in the southern Malay peninsula is low; the peak horizontal acceleration with 10% probability of exceedance in 50 years being 5% g (Petersen et al., 2004). However, although Singapore lies some 700.0 kilometres (km) from the nearest tectonic margin, long-period ground motions induced by large events on the Sumatran subduction interface have historically been felt in the nation (Pan and Sun, 1996). More recently, the $M_w = 8.6$ April 11, 2012 earthquake off of the west coast of north Sumatra induced swaying of taller structures in the city that was clearly noticeable to occupants, and prompted some 126 reports of Modified Mercalli Intensity of 2 (USGS, 2012). Also, simulation studies indicate that high-rise structures on soft-soil sites in Singapore may be at risk from long-period ground-motions if they are of considerable duration (Megawati and Pan, 2009). Such ground-motions are likely in the event of a large ($M_w > 8.0$) earthquake on the Mentawai segment of the Sumatran megathrust. This segment, which is the closest part of the megathrust to Singapore, has not fully ruptured since 1797 (McCloskey et al., 2010), and super-cycle patterns indicate that it could produce a large event in the coming decades (Sieh et al., 2008). Because of the extant hazard of long-period ground motions to Singapore, it is important to understand the velocity structure beneath the city and how it might respond to seismic waves.

Singapore's Meteorological Service Division operates a seismic network consisting of one very-broad-band station (BTDF) housing a Streckeisen STS-2/VBB seismometer and four teleseismic stations (BESC, KAPK, NTU, PTK) housing Kinemetrics WR-1 seismometers located in a rough east–west line across the island (see Fig. 1). The frequency response of the STS-2 instrument is flat between 0.002 Hertz (Hz) and 10.0 Hz, while the WR-1 instruments are flat between 0.1 Hz and 20.0 Hz. Data from this network are shared with other regional networks and with the Global Seismic Network, where they are available through the IRIS consortium. Despite being operational since 1996, little work has been done to characterise the crustal thickness and velocity structure beneath the network (Walling et al., 2010). Such analysis is needed in order to develop velocity models for Singapore that will be useful for seismic hazard studies such as ground-motion simulations. Additionally, such velocity models will add to the existing global

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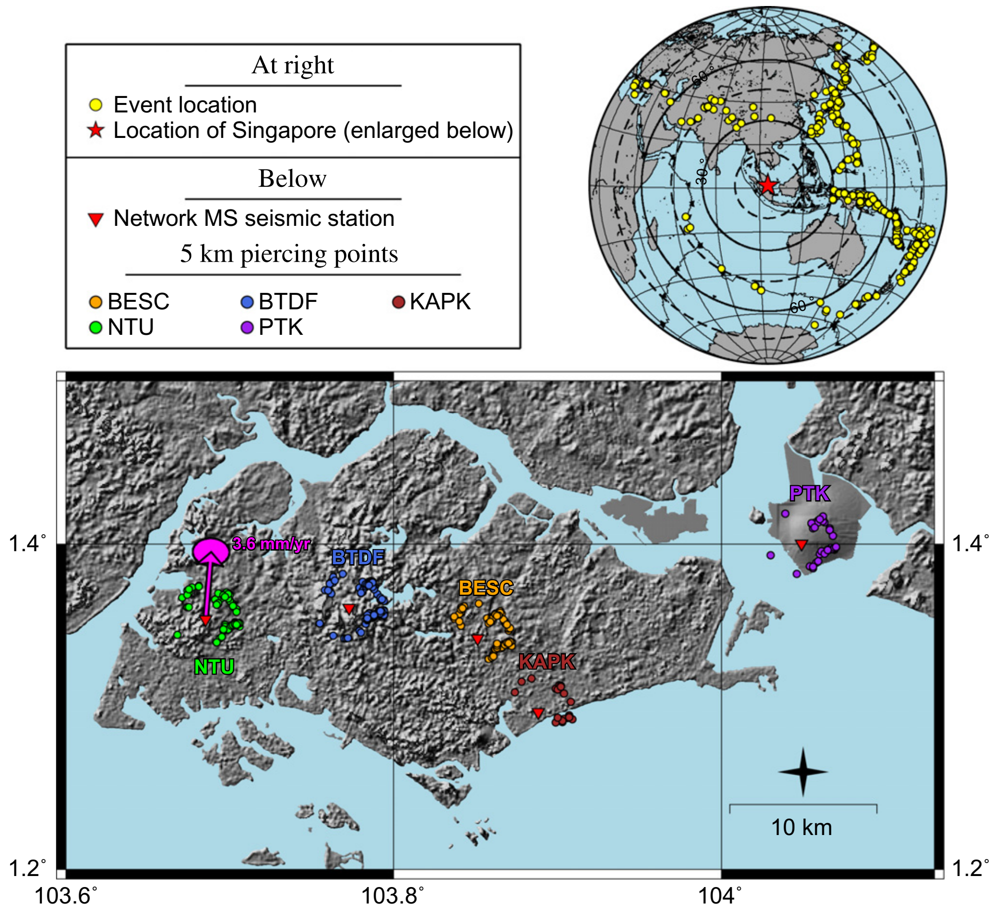

Fig. 1. Study area showing the locations of the five stations that comprise Singapore's seismic network. The globe shows the locations of the teleseismic events that were used to compute receiver functions. The five kilometre piercing points of teleseismic observations, calculated by assuming a 6.0 km/s crustal velocity, are plotted, colour-coded for each station. The motion of the continuous GPS station located at NTU relative to the Sunda block is plotted in magenta, with the 95% confidence error ellipse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

database of available crustal thicknesses and velocity profiles. In this study, we investigate the crustal thickness and velocity structure beneath Singapore's seismic network by analysing teleseismic receiver functions and regional surface waves.

1.1. Geologic and seismotectonic setting

The near-surface geology of the main island of Singapore is characterised by three broad regions. The south and southwest is primarily composed of sedimentary rocks of the Jurong formation, the central region consists of the Bukit Timah granite and the Gombak norite, while the east of the island is primarily covered by the Old Alluvium formation of Quaternary sediments (Rahardjo et al., 2004). Recent alluvial deposits of the Kallang formation are distributed throughout the island. Because of the regions humid tropical environment, significant weathering has occurred to these formations, resulting in extensive deposits of residual soils (Rahardjo et al., 2004). On a more regional scale, Singapore is located, along with Peninsular east Malaysia, within the Indochina terrane to the south east of the Bentong-Raub suture zone (Metcalfe, 2000). This terrane likely separated from Gondwana during the Devonian.

Singapore is located within the tectonically stable Sunda shelf. This is the continental shelf of southeast Asia, and is considered to be distinct from the Eurasian plate due to significant relative motion between the two induced by the collision of India with Asia (Bock et al., 2003). A continuous GPS station located in the west of Singapore (see Fig. 1) indicates 3.6 mm per year of motion to the northeast. The closest likely source zone for significant seismic events is the strike-slip Great Sumatran fault, whose nearest segment is more than 300.0 km away from Singapore. The largest earthquakes produced by the Sumatran fault are likely to be less than a moment magnitude of 8.0 (Natawidjaja and Triyoso, 2007). Therefore, the most salient seismic hazard to Singapore is a great earthquake ($M_w > 8.0$) on the Mentawai segment of the Sumatran megathrust.

2. Receiver functions

The analysis of teleseismic receiver functions has become a routine tool to investigate the depth of discontinuities beneath 3-component seismic stations, and has been undertaken in diverse tectonic environments, e.g., Langston (1977), Ammon and Zandt (1993), Searcy et al. (1996), Dugda et al. (2007), Park et al. (2009), Lloyd et al. (2010), and Macpherson et al. (2012). Receiver functions are time series that have been derived by deconvolving the vertical components from radial components of 3-component recordings. The deconvolution removes the source factor, and because *P*-to-*S* converted waves have higher amplitudes in the radial component than the vertical, results in a time series that is primarily a function of the discontinuities beneath the station (Ammon, 1991). Receiver functions may be modelled to provide constraints on crustal thickness and depth to discontinuities and may be combined with complimentary data sets, such as surface-wave dispersion curves, in order to estimate sub-station velocity structure.