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利用城市通信光缆进行地震观测和地下结构探测

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摘要 在城市地区开展地震观测和地下结构探测有助于提升城市防震减灾能力和城市地下空间利用能力. 然而城市地区密集的建筑和频繁的人类活动一定程度上阻碍了在城市地区开展地震观测. 利用近年来发展的分布式声波传感技术在云南省宾川县城区开展实验, 以探索城市地区地震观测新方法. 总长5.2 km的地下通信光缆被分成上千个传感单元(单元间隔为数米). 光缆记录信号中可以识别出车辆运动、气枪震源、人工落锤等不同振动信号. 利用从光缆记录的背景噪声, 提取了面波信号, 并获得了地表200 m以内的横波速度结构, 这为工程场地评价提供了重要信息. 以上初步结果表明, 城市地下通信光缆为城市精细结构探测、交通监测和地震预警等工作提供了一种新型观测手段.

关键词 分布式声波传感, 通信光缆, 地震观测, 地震成像, 城市地区

随着社会发展的进程, 城市集中了越来越多的社会财富和人口, 让城市变得更加拥挤且脆弱. 城市高效运行和安全发展紧迫要求提升地下空间利用效率和地震灾害风险抵御能力, 这两个能力的提升都依赖于我们对城市地区地下精细结构的认识[1,2]. 城市地区精细结构探测主要依赖人工震源地震勘探[3]和被动源成像[4–6]等地球物理方法. 利用地震学方法对城市地下结构进行探测通常需要在地表密集布设地震观测仪器. 然而, 城市地区密集的建筑和频繁的人类活动使得在城市地表布设地震台站进行地震观测变得越来越困难. 因此探索城市地区新型地震观测方法和技术势在必行.

近年来, 一种基于光纤的新型地震观测技术——分布式声波传感(distributed acoustic sensing, DAS)技术迅猛发展[7]. DAS技术是通过测量光纤中后向散射光的相位变化实现光纤动态应变的监测, 进而实现地震波场记录[8]. 目前, DAS技术有能力利用一个解调器(interrogator)在长达近百千米的光缆上实现每2 m一个震动传感单元[9]. 随着光电技术进步, 观测距离和空间密度还可能进一步提升. 利用DAS技术实现的传感器密度高于目前常规地震勘探的检波器密度. 观测密度高、适用范围广等优点使得DAS技术被逐渐应用于地震[10]和冰川[11]等不同场景的观测研究.

最近, 国内学者利用专门铺设的光缆开展了浅层结构探测研究[12,13], 获得了光缆沿线较高分辨率的浅层横波速度剖面. 同时, 城市中遍布的通信光缆为在城市地区开展低成本地震观测和结构探测提供了可能[14]. 结合DAS技术和城市通信光缆, 研究人员成功地观测到天然地震[10,14]、交通[15]及雷电[16]等信号. 国内尚未见报道利用通信光缆进行城市地区地震观测方面的研究. 为探索利用我国城市通信光纤进行地震监测和地下结构探测的可行性, 我们联合中国移动云

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南省宾川县分公司开展了数次野外实验. 本研究介绍了野外实验的初步结果, 并探讨了利用城市通信光缆进行地震观测研究的前景.

为验证城市通信光纤进行地震监测和城市地区地下结构探测的可行性, 我们分别于2018年12月29~31日和2019年12月1~8日利用中国移动宾川县分公司提供的通信光缆进行了两次观测实验. 实验中使用了铺设于宾川县城金牛路和太和路边的一条通信光缆(128根光纤)中一根备用光纤, 光缆呈L型展布全长约5.2 km(图1(a)). 该光缆穿过预埋于地下(~30 cm)的穿线管, 并每隔一段距离(~200 m)经过一个检修口. 穿线管在检修口处由水泥浇筑固定, 其余部分为土埋(图1(b)). 两次实验采用了不同的解调器. 第一次实验中长5.2 km的光纤被划分为1280个震动传感道(道间距为4 m), 信号的采样率为每秒5000点. 第二次实验中, 道间距设为7.5 m. 为获得传感道的绝对坐标, 在光缆沿线每隔100 m进行锤击. 锤击位置由手持GPS确定, 并被赋予锤击信号最强的道. 其他记录道的位置则根据道间距以及锤击道位置通过空间插值获得.

在距离光缆约8 km处建有宾川气枪震源(图1(a)插图), 该震源可以产生相当于0.7级地震的地震波信号[17,18]. 气枪震源重复性高, 可以用于地下介质微弱变化的监测研究[19], 同时也为光纤观测提供"已知"地震信号[20,21]. 第一次实验期间, 分3个时间段(29日夜~30日凌晨、30日下午和30日夜~31日凌晨)开展了连续观测实验, 每次3~4 h, 累计观测时长约10 h, 观测总数据量约2 TB. 第二次实验期间, 在太和路段光缆沿线48个位置进行了人工重锤激发, 并且进行了111次气枪震源激发.

在连续观测实验期间, 我们记录到了多种不同来源的震动信号. 以下分别介绍通过初步分析得到的交通信号、背景噪声互相关面波信号, 以及人工震源产生的地震信号.

(ⅰ) 交通信号. 由于通信光缆布设于道路下方, 城市交通信号的振动必然会在光纤连续记录中留下印记[15]. 从随机选取的一段光纤记录中(图2), 可以清楚地识别出两组分别以~42和38 km/h移动的信号, 这可能对应了在太和路上北向移动的车辆. 移动源还激发了速度约为300 m/s的沿地表传播的地震波(类似行船激起的波浪, 图2绿色和蓝色虚线). 以上记录显示了利用通信光缆进行交通监测的可能性[15], 同时这些信号源也可能应用于地下速度结构研究.

(ⅱ) 利用光纤记录进行背景噪声成像. 通过背景噪声互相关函数(noise correlation function, NCF)获取台站之间的经验格林函数并进行地下结构成像[22]是21世纪地震学的一个重要进展. 该技术被广泛应用于不同尺度的结构探测[4]. 利用光纤记录的20 min噪声信号计算了不同道之间的NCF(图3(a)). 在NCF中可以清晰地分辨出两支速度约为300 m/s的信号(图3红色虚线), 该信号被推测为沿地表传播的Rayleigh波. 通过测量Rayleigh波的传播速度和频率的关系(图3(b)), 可以反演得到地下200 m的横波速度(图3(c)). 宾川盆地近地表横波速度在280~430 m/s, 属于典型的沉积盆地横波速度.

(ⅲ) 气枪震源及锤击信号. 通过背景噪声互相关分析, 可以得到地下200 m的横波速度. 为获得更深部速度结构及纵波波速结构信息, 还需要利用天然地震或人工震源激发的信号[23,24]. 在光纤观测期间, 宾川地区地震目录中无天然地震记录. 我们利用宾川气枪震源[25]检验光纤对小地震的记录能力. 由于城市地区噪音高且气枪震源能量弱(相当于0.7级地震)[17,18], 很难在单次激发记录(DAS或短周期地震仪)中识别出气枪信号. 利用气枪震源重复性高的优点[19], 将

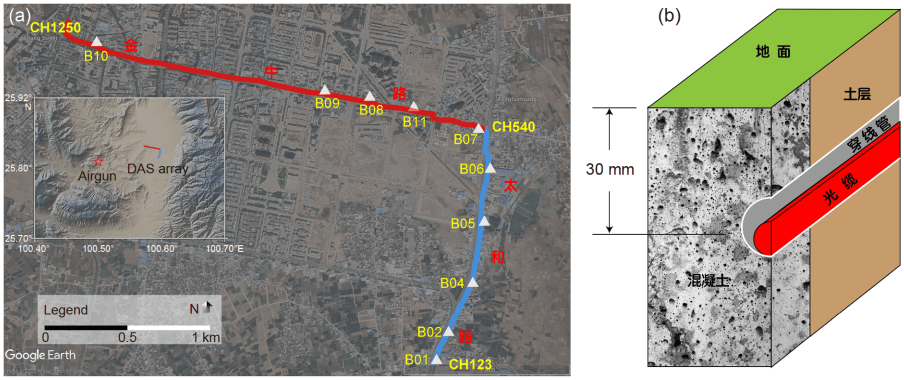


图 1 通信光缆分布示意图. (a) 通信光缆分布, 所使用光缆位于宾川县城区金牛路(红色粗线)和太和路(蓝色粗线)下方. 节点道号用黄色数字表示. 插图显示了气枪震源(红色五角星)和光缆(DAS array)的相对位置. 在光缆沿线布设了10套三分量短周期地震仪(白色三角形)以对比记录信号. (b) 通信光缆架设示意图. 光缆(红色)松散地穿过穿线管(灰色), 穿线管埋于土中, 在检修口处穿线管由混凝土浇筑

Figure 1 Sketch of the used telecom optical fiber cable. (a) The telecom optical fiber cable used in this study is located beneath the Jinniu Road (thick red line) and Taihe Road (thick blue line) in the Binchuan County, Yunnan Province. The inset indicates the relative position between the Airgun source (red star) and optical fiber cable (Das array). Ten 3-component short period seismometers (white triangles) were deployed along the cable. (b) The sketch illustrates the deployment of optical fiber cable. Cables (red) are loosely laid in the conduit. The conduit was buried ~30 cm beneath the surface and was cemented in the manhole

波形记录根据气枪激发时刻进行叠加得到伪记录剖面(图4(a)). 在叠加记录中可以看到清晰的S波信号, 在某些通道上光纤观测信号与共点的短周期地震仪记录具有很高的相似性(图4(a)). 由于光纤主要对沿线(本实验中为水平)方向敏感[7], 因而光纤记录的S波要显著强于P波[21]. 气枪震源产生的S波已经被广泛观测并应用[19,25,26], 但是气枪震源激发S波的机理尚未完全理解.

重锤也是浅部地下结构探测的常用震源. 为测试通信光缆对锤击信号的记录效果. 我们沿太和路在48个位置开展了重锤(8.16 kg)激发实验, 每个位置进行5次锤击. 在锤击剖面记录中(图4(b))发现单次重锤激发信号可以传播约100 m, 并能分辨出两组视速度约400和320 m/s的信号. 锤击记录剖面较为复杂, 这可能与光纤的接收条件和地下结构特征有关, 相关研究有待进一步深入.

以上初步实验结果表明, 将DAS技术应用于地下通信光缆可以实现城市地区超密集地震观测. 与专门布设的光缆[20]及地震仪[21]相比, 通信光缆的记录信号信噪比较低(图4(a)). 光缆记录的信噪比与光缆的布设方式密切相关, 通信光缆穿过穿线管时并未进行任何固定, 震动信号是经过管/缆之间摩擦力传递的[7]. 光缆与线管之间的接触差异还会影响不同道信号的信噪比及一致性(图4). 光缆布设方式对信号的影响有待积累更多观测数据并开展深入研究[14].

近地表横波速度结构对于准确评估区域(特别是盆地地区)地震灾害风险具有重要意义, 是工程地震学研究的重要内容之一. 根据光缆记录获得的地下200 m以内横波速度(280~430 m/s), 与我

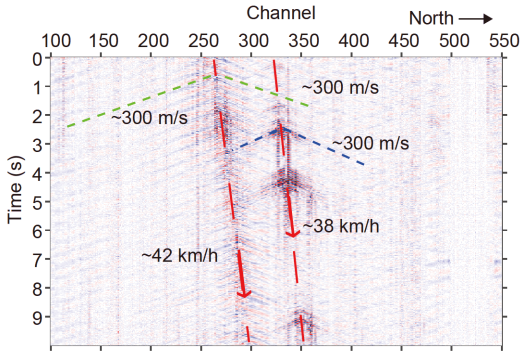


图 2 2018年12月30日下午15时12分通信光缆(道号100~550, 主要位于太和路, 图1(a))观测到两组强振动信号(红色虚线表示), 分别对应了以约42和38 km/h速度向北移动的信号(红色剪头所示). 同时移动源也会激发以~300 m/s(绿色及蓝色虚线)向两侧传播的信号, 信号的传播速度与地表的面波速度接近

Figure 2 Seismic records by the telecom optical fiber cable (channels 100−550, located along the Taihe Road, Fig. 1) on 15:12 Dec. 30th, 2018 show two groups of strong vibration moving northward with speeds of 42 and 38 km/s (red arrows). The moving source generated signals propagating outward with speed ~300 m/s (green and blue dashed lines), close to the surface wave velocity of the uppermost layers

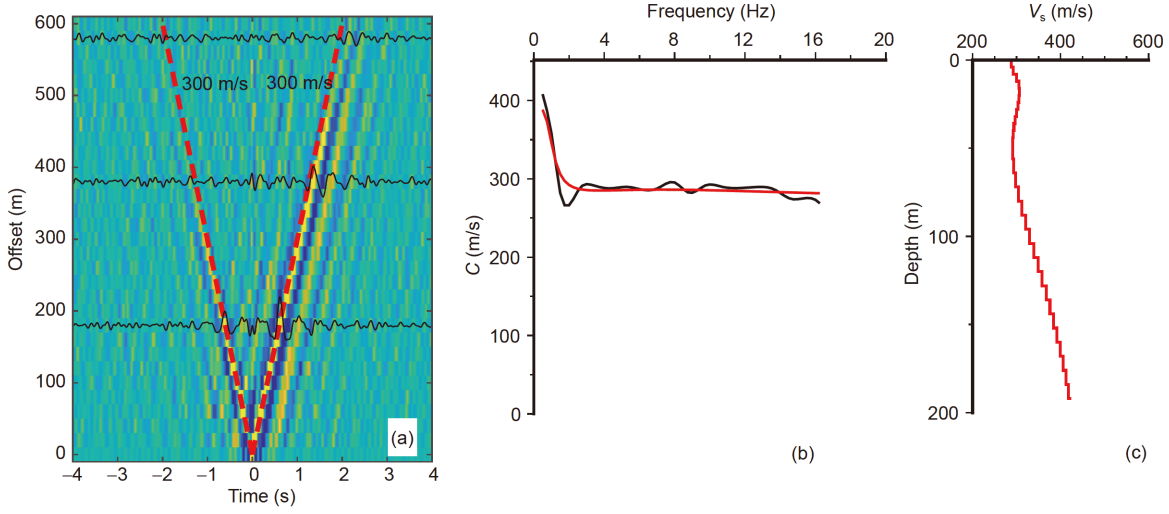


图 3 利用光缆记录噪声成像地下结构. (a) 利用光纤记录的20 min噪声信号获得的互相关函数(1~8 Hz滤波). 正负时间表示沿两个不同方向传播的信号. 黑色曲线表示了该距离上的NCF波形. (b) 面波速度与频率的关系(频散曲线), 其中黑色和红色分别为观测频散曲线和根据反演速度模型(c)计算的理论频散曲线. (c) 根据观测频散曲线(b)反演的一维横波速度结构

Figure 3 Imaging subsurface structure with ambient seismic noises recorded by DAS. (a) The noise correlation function (1−8 Hz filtered) profile obtained from 20-min long ambient noise DAS records. Positive and negative times indicate signals propagating along two different directions. Black curves represent NCF waveforms at corresponding distance. (b) Dispersion curves extracted from the NCFs, black and red lines represent observed dispersion curve and dispersion curve calculated from the velocity model in (c), respectively. (c) One-dimensional shear wave velocity inverted from the dispersion curve in (b)

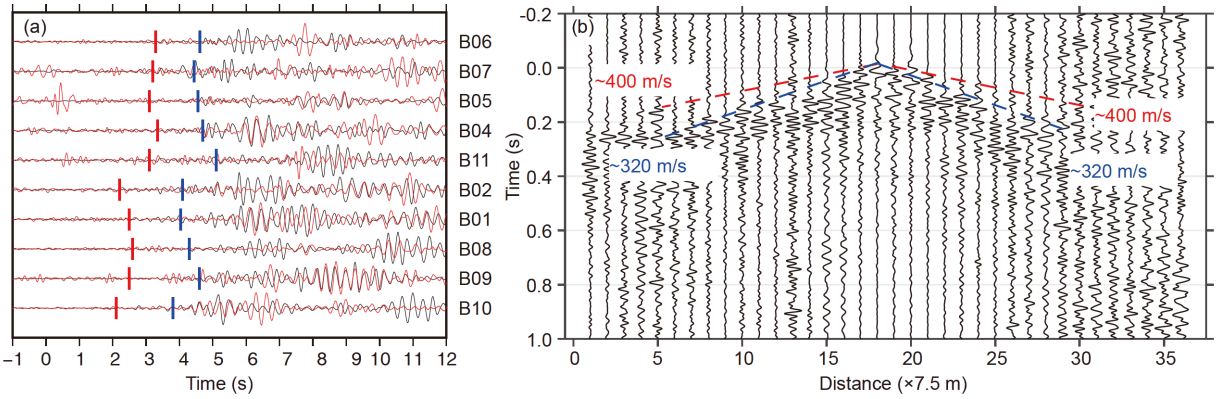


图 4 通信光缆(道间距7.5 m)记录到的气枪震源信号(a)和人工落锤信号(b). (a)中红色和黑色分别为DAS和短周期地震仪记录的叠加气枪震源信号(2~8 Hz), 布设于金牛路和太和路的地震仪分别取东西向和南北向记录进行对比. 红色和蓝色短竖为依据三分量短周期地震仪记录, 并参考偏振分析拾取的P和S波到时, 拾取的到时与由区域速度结构模型[26]计算的上地壳折射Pg和Sg的到时吻合. (b) 一次人工锤击实验得到的记录剖面(20~60 Hz). 红色和蓝色虚线分别标记了视速度400和320 m/s

Figure 4 Seismic signals from airgun (a) and electric hammer (b) recorded by the DAS. (a) Airgun signal recorded by the DAS. Red and black lines are stacked records (2−8 Hz) from DAS and co-located short period seismometers. East-west and North-south components are used for seismometers along the Jinniu Road and Taihe Road, respectively. Red and blue short bars are manually picked P and S arrivals from seismometers according to particle motions. The P and S arrivals are in agreement with the refracted Pg and Sg wave arrivals calculated with local velocity structure[26]. (b) Seismic profile (20−60 Hz) from one hammer shot. Red and blue dashed lines mark the apparent velocities of 400 and 320 m/s, respectively

们利用密集台阵获得的结果吻合[27]. 宾川盆地的横波速度位于二类场地[28]的横波速度范围. 利用城市通信光缆可以进行地震观测并服务于城市地区浅层结构的勘查.

利用城市通信光缆进行地震监测不仅可以获得区域地下结构, 同时也为监测地下水位[14]和城市交通监控(图2)等提供了新手段. 除了城市通信光缆之外, 海底光缆也被用于高密度海洋地震观测研究[29]. 总之, 相对于传统地震仪, 分布式光纤观测具有密度高、性能稳定、应用灵活等优点, 为在复杂(如城市、矿区)和极端条件(如海底、深井)下开展地震观测提供了新手段.

本研究介绍了将DAS技术应用于城市通信光缆进行地震观测和结构成像的初步结果. 城市通信光缆成功地记录到城市交通、地震背景噪声和人工震源等信号, 并实现了近地表结构成像. 本研究结果显示, 将DAS技术应用于城市通信光缆为城市地区地下精细结构探测和交通监测等提供了一种新型观测手段. 随着高速互联网和城市化进程的发展, 通信光缆的覆盖范围和密度都将大大增加, 这为DAS技术提供了更广阔的应用空间.

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Summary for “利用城市通信光缆进行地震观测和地下结构探测”

Seismic observation and subsurface imaging using an urban telecommunication optic-fiber cable

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Seismic observation and subsurface imaging are of key importance in mitigating the seismic hazards and exploiting subsurface spaces in urban areas. However, the urban seismic observation is, to some extent, hindered by more and more populations and facilities in urban areas. To develop new methods for urban seismic observation, we carried out several field experiments in Binchuan city, Yunnan Province. In the experiments, we applied the distributed acoustic sensing (DAS) technique to an urban telecommunication optic-fiber cable to monitor ground motions. The DAS technique was rapidly developed and applied to seismic investigations of different scales during the past several years. Binchuan city is located in the Binchuan basin, which is one of the largest sedimentary basins in western Yunnan. The Binchuan basin is well studied and equipped with seismic instruments, including a Fixed Airgun Signal Transmission Station (FASTS). The FASTS can radiate highly repeatable seismic signals with seismic energy equivalent to a magnitude 0.7 earthquake; the seismic signal can be used to test the sensitivity of seismic instruments during the seismically quiet period.

During the experiment, a 5.2 km long optic-fiber cable buried along two local roads was parted into ~1000 sensing channels with a channel spacing of several meters, and the cable vibration was continuously digitized with a sampling rate of 5000 sps (samples per second). The DAS registered the ground motions originating from various sources. We clearly identified some vibrations moving with a speed of ~40 km/h, which likely originate from moving vehicles along the road. During the experiment, we fired 111 airgun shots. The seismic signal from each single airgun shot was invisible in the DAS records, but clearly emerged after stacking. The airgun signals recorded by the DAS show similar features as recordings from co-located short period seismometers. To test the feasibility of imaging the subsurface with DAS, we also hammered the ground at 48 points along the road with an 8 kg hammer. The DAS clearly recorded the hammer signal traveling with apparent velocities of 300−400 m/s to a distance of ~100 m. Furthermore, we reconstructed the empirical Green's function from continuous DAS record. We are able to retrieve high-quality surface wave signals and corresponding dispersion curves (the relationship between surface wave velocity and frequency) from 20-min long noise recordings. Then based on the dispersion curves, we obtained the shear wave velocity structure of the uppermost 200 m. The shear wave velocity of the uppermost layer is important for the soil classification in engineering seismology. The shear wave velocities of the uppermost 200 m range from ~280 to 430 m/s, indicating a class II soil in the Binchuan basin.

Our preliminary results revealed the feasibility of seismic observation using an urban telecommunication optic-fiber cable, which provides a novel method for many urban seismic applications, such as fine subsurface structure imaging, traffic monitoring, and earthquake early warning.

distributed acoustic sensing, telecommunication optic-fiber cable, seismic observation, seismic imaging, urban area

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