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2017 年 9 月 3 日朝鲜地下核试验的地震学鉴别和当量估计

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摘要 北京时间 2017 年 9 月 3 日 11 时 30 分在朝鲜境内发生一次强烈地震事件. 利用区域地震数据中纵波和横波的振幅谱比值, 我们确认这是一次爆炸事件. 8 min 后在同一位置发生一次余震, 确定是事后由爆炸产生的腔体坍塌引起的陷落地震事件. 利用区域震相 Lg 波和 Rayleigh 波获得此次核试验的体波和面波震级分别是 m_b(Lg)=5.6±0.2 和 M_s=5.1±0.2. 采用体波震级与当量的经验关系式, 假定爆炸与周围岩体完全耦合而且置于正常埋藏深度, 此次朝鲜核试验的地震学当量约为 56 kt. 考虑到震级误差, 当量估计的不确定性范围是 30~100 kt. 如果实际埋藏深度达到 1000~2400 m, 则爆炸当量可能达到 100~200 kt.

关键词 朝鲜, 地下核试验, 区域地震波, 鉴别, 当量估计

中国地震台网测定, 2017年9月3日 11 时 30 分在朝鲜境内 41.35°N, 129.11°E处发生6.3级地震(疑爆), 震源深度0 km. 该次事件在中国东北和华北大部分地区引起强烈震感. 事发1 h后, 朝鲜政府宣布这是该国成功进行的氢弹试验. 此前朝鲜已于2006, 2009, 2013, 2016年1月和9月分别进行了5次地下核试验[1~5]. 本次试验是第6次, 爆炸威力远大于前面的. 将此次事件与之前5次核试验在牡丹江地震台(MDJ)的地震记录进行比较, 发现波形高度相似, 均具有P波能量较强, Lg波能量较弱, Sn波不发育, 短周期(3~5 s)Rayleigh面波能量强等特征, 呈现显著的浅源爆炸特征(图S1). 主震之后约8 min, 在同一位置发生了一次余震事件, 推测为爆炸产生的空腔在事后坍塌所引起. 图S1中也给出了该次余震在MDJ台的地震图. 由于坍塌与爆炸发生在同一地点且在同一台站接收, 各种震相具有相同的走时. 但由于二者的震源时间函数和震源机制不同, 各种震相的优势频率和相对激发强度存在很大差别.

我们收集中国地震台网(CNDSN)和全球地震台网(GSN)的区域波形资料, 调查2017年9月3日朝鲜主震和余震事件的地震学特征, 主要包括: (1) 利用P/S型谱比值方法[1,3~9]确认2017年9月3日11时30分的主震事件是爆炸, 8 min后发生的余震是塌陷地震; (2) 利用区域地震Lg波和Rayleigh波计算体波和面波震级[10~15]; (3) 事件的地震学当量估计[1~5,7,16,17]. 为叙述方便, 对6次朝鲜核试验依时间顺序称为DPRKT1, 2, 3, 4, 5和6.

1 事件类型鉴别

地下核试验与天然地震不同, 前者是爆炸源, 主要产生压缩P波, 剪切S波的能量较弱; 后者是由断层错动产生的位错源, 主要产生剪切S波, 作为压缩波的P波能量较弱. 分析P波和S波的辐射, 可以识别地下核试验和天然地震事件[1,3~5,18~23]. 对2006年10月9日的朝鲜首次核试验, Richards和Kim[6]利用区域P波和S波的振幅谱比

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值Pg/Lg判断DPRKT1是一次爆炸事件．然而，他们用的单台数据得到的结果仅适用于9.0~15.0 Hz的高频频谱．Zhao等人[1]对数据处理方法作了改进，对我国东北地区丰富的区域地震记录，经过振幅-频率-距离校正后[23]在全台网内进行叠加处理．多台方法拓展了数据的频带范围，减少了单台观测造成的数据起伏．在高于2 Hz的频带，该方法能够将所有朝鲜地下核爆炸从地震事件群组中识别出来[1,3~5]．

根据朝鲜核试验场(DPRKTS)的6次核爆事件及邻近地区4个天然地震在中国东北和朝鲜半岛11个地震台站所记录的垂直分量波形资料，我们分别计算了不同类型的P波和S波的振幅谱比值Pg/Lg，Pn/Lg和Pn/Sn，经过距离校正后叠加获得台网平均振幅谱比值．已知事件的平均振幅谱比值可作为识别朝鲜半岛地震和核爆事件的依据．图1显示了核爆与地震事件各自振幅谱比值的特征．蓝色曲线明显落入爆炸震源的群组，应是一次爆炸事件．绿色曲线具有非常独特的谱比值结构．显然不是爆炸震源但也不完全等同于地震震源．在6 Hz以下的低频部分，它的谱比值接近爆炸震源的结果．而在高频段谱比值更接近天然地震的结果．

2 体波和面波震级

Lg波是大陆地壳中在区域地震距离内(2°≤Δ≤30°)可以明显观测到的稳定震相，衰减慢，适用于测定体波

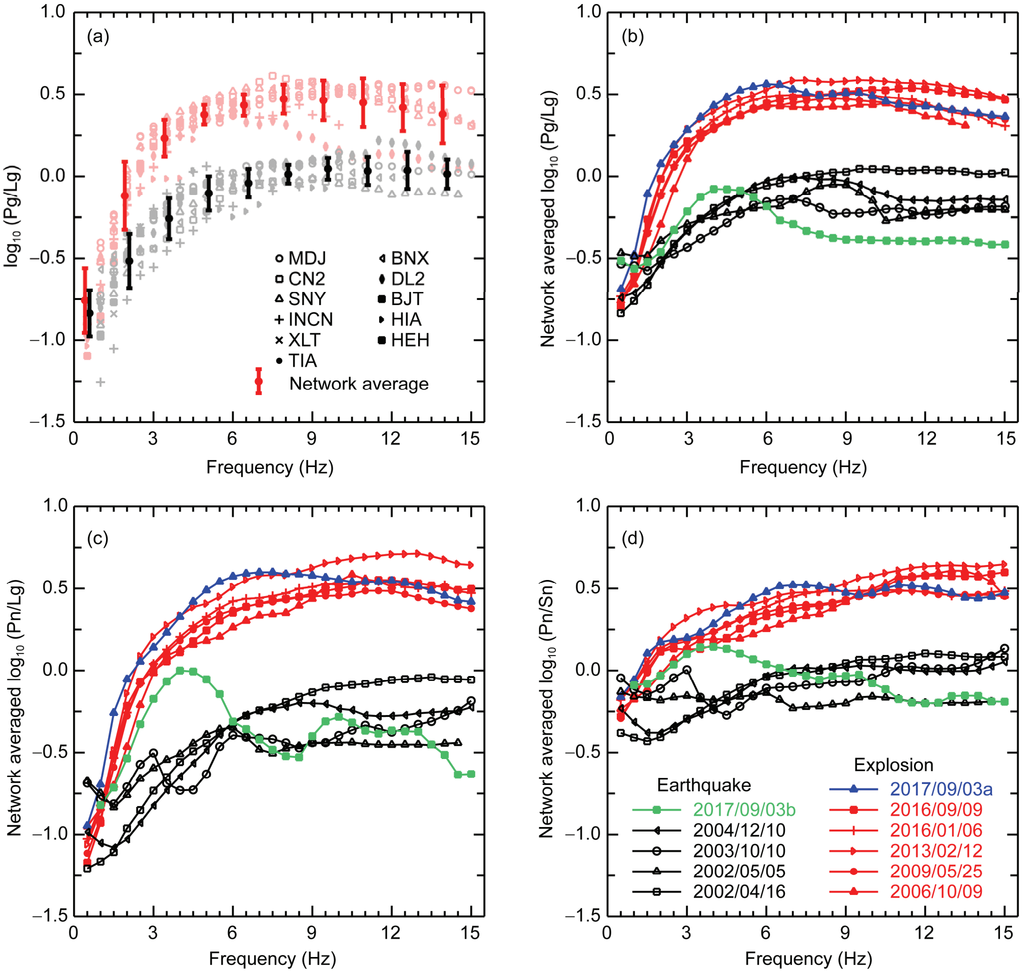

图1 核爆与天然地震事件的频谱比[5]．(a) 单一事件单台得到的Pg/Lg比值，浅红色和灰色符号分别来自2009年朝鲜核试验(DPRKT2)和2002年4月16日发生在朝鲜核试验场附近的天然地震．红色和黑色的实心圆和误差棒为对台网内多台数据得出的均值和方差．(b)~(d) 各次事件得到的Pg/Lg，Pn/Lg和Pn/Sn频谱比的台网平均值，红色曲线来自历史核试验，黑色曲线为天然地震．蓝色曲线来自2017年9月3日11时30分的事件，该事件显然落入爆炸事件的群组．8 min后的余震事件用绿色曲线表示，推测为爆炸产生的空腔坍塌所引起

Figure 1 Spectral ratios for selected regional phases[5]. (a) Comparisons of Pg/Lg spectral ratios for DPRKT2 and an earthquake occurred on April 16, 2002 near the DPRK nuclear test site. Light colored symbols indicate measurements from individual stations. Solid circles and error bars show network averaged values and standard deviations. Red and black colors indicate explosion and earthquake sources, respectively. (b)–(d) Pg/Lg, Pn/Lg and Pn/Sn spectral ratios from 5 previous DPRK nuclear tests (red), 4 nearby earthquakes (black), the event at 11:30 on September 3, 2017 (blue) and the 8 min later aftershock (green)

震级和估计核爆当量[24,25]. Zhao等人[1]利用24个区域地震事件标定了中国东北和朝鲜半岛由8个台站组成的区域台网的P波和Lg波的体波震级，之后又将其扩展到包括11个台站和102个地震事件[5]. 标定过程中使用的地壳衰减模型从简单的区域平均Q值发展到具有横向变化的宽频带Q值模型[26,27]. 图S2(a)是朝鲜核试验场及周边的地图，包括了台站位置和所有历史地震事件. 射线路径上所标的Q值是沿大圆路径的平均值. 对2017年9月3日朝鲜核试验及其余震，我们用该台网的垂直分量Lg波得到它们的体波震级m_b(Lg)分别为5.56±0.20和3.95±0.04.

面波震级不仅是事件大小的量度，而且可以通过与体波震级比较作为区分核爆与地震的判别工具[28,29]. 基于图S2(a)所示的区域地震台网，我们采用周期8~25 s的Rayleigh波最大振幅确定了研究区内104个事件的面波震级M_s(Rayleigh)，并连同它们的体波震级m_b(Lg)一同表示在图S2(b)中. DPRKT6及其余震的面波震级M_s分别为5.10±0.25和3.95±0.08. 从图S2(b)中可以看到，表示核爆的五角星和表示地震的空心圆在很大范围内重叠在一起，表明在朝鲜半岛地区通过m_b:M_s区分人工爆炸和天然地震事件的方法并不适用. 这与前人的研究结果是一致的[12,28~31].

3 爆炸当量估计

根据上述由区域地震台网确定的体波震级，通过完全耦合的震级-当量经验公式[32]得到相应的地震学当量为56 kt，如图2(a)所示. 将震级估计的误差换算到当量估计中，误差范围是30~100 kt. 由于缺乏实际的震源深度信息，这一结果是基于埋藏深度符合正常的当量-深度比例关系得到的估计值. 为了防止核泄露造成环境污染，地下核试验的埋藏深度常常超过正常比例深度. 实际的核装置的地下埋藏模型包括平硐、斜硐和平硐+竖井模型. 平硐模型是指从山体一侧水平挖掘遂道进入山体放置核装置. 斜硐是向下倾斜挖掘遂道，竖井则是进入山体后向下挖井扩大埋深. 因此，通常通过精确定位获取高程，利用其与遂道洞口的高程差估计的是最小埋深[5,16]. 此

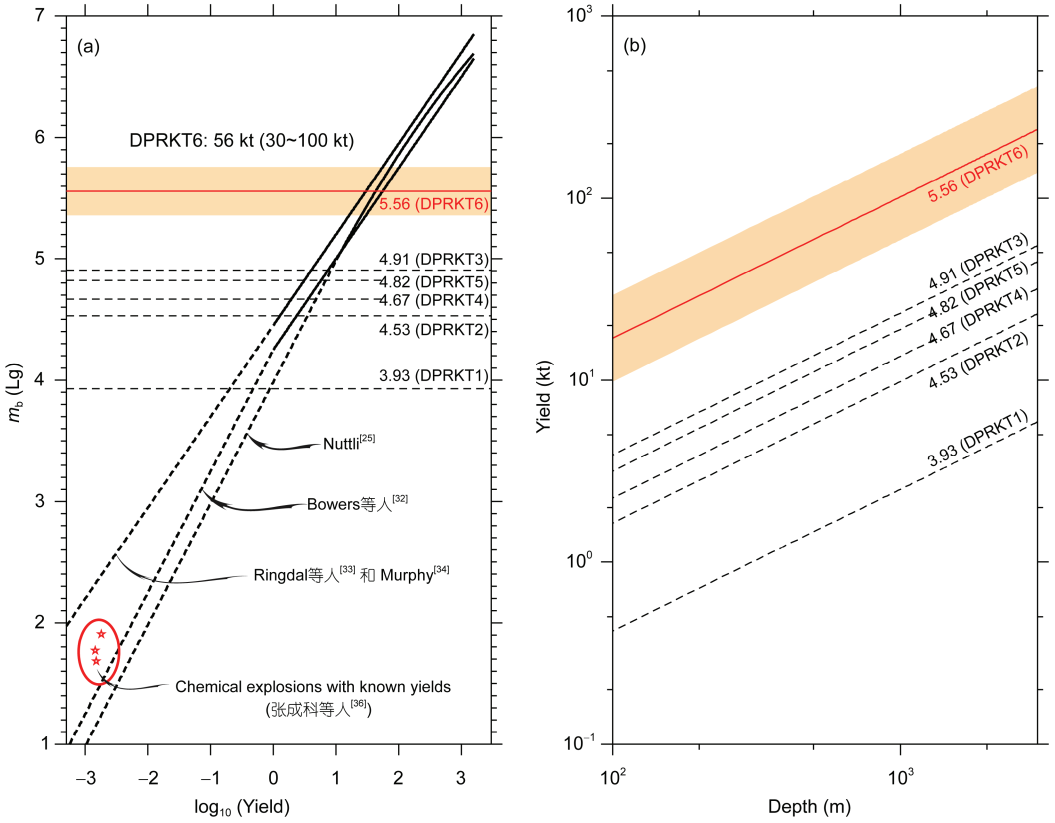

图 2 朝鲜核试验场震级-当量经验曲线和当量与埋藏深度之间的折衷关系曲线. (a) 在朝鲜核试验场进行当量估计的震级-当量经验曲线. 其中实线部分为以大量数据为基础的关系曲线，虚线段为少量数据支持的延伸线; DPRKT1~5 为 5 次历史朝鲜地下核试验, DPRKT6 为 2017 年 9 月 3 日朝鲜爆炸事件. (b) 朝鲜地下核试验当量与埋藏深度之间的折衷关系曲线[16,35]

Figure 2 Empirical magnitude-yield relations and variations of the yield versus depth of burial trade-off curves for DPRK nuclear tests. (a) Empirical magnitude-yield relations; sections supported by observations are illustrated as solid lines and extrapolations are illustrated as dashed lines. The horizontal red line indicates the estimated magnitude, m_b(Lg)=5.6 for DPRKT6. Three chemical explosions with known yields (stars) are also illustrated. (b) Variations of the yield versus depth of burial trade-off curves for DPRK nuclear tests[16,35]

次核试验的当量较大，有可能为平硐+竖井的埋藏方式．如果埋藏深度达到1000~2400 m，根据震级-深度-当量的经验关系[16,33]，此次核试验的当量有可能达到100~200 kt．

4 讨论和推论

根据中国东北和朝鲜半岛地区的区域地震资料，我们对2017年9月3日11时30分和38分发生在朝鲜核试验场的两次事件进行了地震学调查．采用P/S型振幅谱比值的方法确认了前者是一次人为爆炸事件，与前几次朝鲜核爆产生的地震信号高度一致．后者是爆炸后产生的局部坍塌事件，它的振幅谱比值具有比较独特的形态．在6 Hz以下的低频段，振幅谱比值与爆炸源相近；在6 Hz以上的高频段与地震群组类似．考虑到朝鲜核试验场所处的位置以及场地地质条件，并利用3个小型化学爆炸事件，我们选择Bowers等人[32]给出的大陆地区震级-当量经验公式估计朝鲜核爆的当量．如果这次爆炸在正常埋藏条件下进行，其地震当量约为56 kt，误差范围是30~100 kt．如果爆炸采用了超深埋藏则DPRKT6的地震学当量有可能超过100 kt．

致谢 地震波形资料从中国地震台网中心(CENC)和美国地震联合会数据管理中心(IRIS DMC)收集．中国地震局地球物理勘探中心的张先康研究员提供了中国东北地区用于地震测深、已知爆炸当量的化学爆炸事件的参数．图件绘制采用 GMT 软件(www.soest.hawaii.edu/gmt)[37]．

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补充材料

图 S1 牡丹江地震台(MDJ)记录到的朝鲜 6 次地下核试验以及第 6 次核试验后坍塌事件的垂直向速度波形

图 S2 中国东北、朝鲜半岛及邻近地区的地图(a)和中国东北和朝鲜半岛地区 104 个事件的体波和面波震级比较(b)

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Summary for “2017年9月3日朝鲜地下核试验的地震学鉴别和当量估计”

Seismological discrimination and yield estimation of the 3 September 2017 Democratic People’s Republic of Korea (DPRK) underground nuclear test

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At 11:30 on September 3, 2017 (Beijing time), a strong earthquake occurred in Democratic People’s Republic of Korea (DPRK). International seismic monitoring agencies, e.g., the China Earthquake Network Center (CENC) and the United States Geological Survey, suspected that it is an explosion. Based on seismic data from the China National Digital Seismic Network (CNDSN) and Global Seismic Network (GSN), we investigated characteristics of this event and an aftershock 8 min after the main event.

The P- and S-wave excitation functions of explosion and earthquake sources are scaled differently. Therefore, the P/S-type spectral ratios can be an effective discriminant for separating explosions from earthquakes. Using the P/S spectral ratios Pg/Lg, Pn/Lg and Pn/Sn as discriminants, we confirmed the 3 September 2017 event was an explosion. For the aftershock occurred after the main event, we identified it is a collapse, likely caused by the failure of the explosion generated cavity.

Using a pre-calibrated regional seismic network in Northeast China and the Korean peninsula, and the regional Lg-wave attenuation model developed previously, we obtained the Lg wave body wave magnitudes for the 3 September 2017 main event and its aftershock to be m_b(Lg)=5.6±0.2, and 3.95±0.04. We used a group of historical events to calibrate the regional network for calculating Rayleigh wave magnitude. After correcting for the site responses, the network averaged surface wave magnitudes for the main shock and the aftershock were obtained to be M_s=5.1±0.2 and 3.95±0.08. To test body-wave versus surface-wave magnitude as a potential discriminant, we compared the M_s (Rayleigh) and m_b (Lg) for all 6 DPRK nuclear explosions and a group of earthquakes in Northeast China and the Korean peninsula. The explosion and earthquake populations were largely overlapped with each other. The above results show that the P/S ratio method is a more effective discriminant than the m_b(Lg)-M_s criterion in Northeast China and the Korean Peninsula.

The seismic yield of an underground nuclear explosion can be estimated from its magnitude using a calibrated empirical magnitude-yield relation. However, the DPRK test site (DPRKTS) is an uncalibrated test site. Considering that the DPRKTS is located at a granite site in a stable geology platform, we adopted the fully-coupled hard-rock site equation used at the Novaya Zemlya test site to calculate the yield at the DPRKTS. The estimated yield for the 3 September 2017 explosion was 56 kt using this relationship and assuming a normally scaled burial depth. Transferring the measurement error of ±0.2 magnitude unit to the yield calculation introduced uncertainties between 30 and 100 kt. However, if the explosion was over buried at depths between 1000 and 2400 m, the yield could be increased to 100–200 kt.

Democratic People’s Republic of Korea (DPRK), underground nuclear test, regional seismic wave, discrimination, yield estimation

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