CHARACTERIZATION OF THE ELECTRIC FIELD CONCENTRATION BETWEEN TWO ADJACENT SPHERICAL PERFECT CONDUCTORS

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Abstract. When two perfectly conducting inclusions are located close to each other, the electric field concentrates in a narrow region in between two inclusions and becomes arbitrarily large as the distance between two inclusions tends to zero. The purpose of this paper is to derive an asymptotic formula of the concentration which completely characterizes the singular behavior of the electric field when inclusions are balls of the same radii in three dimensions.

Key words. electric field, concentration, perfect conductor, adjacent inclusions

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1. Introduction and statement of results. Let \( D_1 \) and \( D_2 \) be bounded, simply connected, and convex domains in \( \mathbb{R}^d \), \( d = 2, 3 \). Suppose that the conductivity of the inclusions is \( \infty \); in other words, inclusions are perfect conductors. We consider the following conductivity problem:

\[
\begin{align*}
\Delta u &= 0 & \text{in } \mathbb{R}^d \setminus (D_1 \cup D_2), \\
u &= C_j \text{ (constant)} & \text{on } \partial D_j, j = 1, 2, \\
u(u(x) - H(x)) &= O(|x|^{1-d}) & \text{as } |x| \to \infty,
\end{align*}
\]

where \( H \) is a given harmonic function in \( \mathbb{R}^d \) so that \( -\nabla H \) is the background electric field in the absence of the inclusions. The constant value \( C_j \) on \( \partial D_j \) is determined by the condition

\[
\int_{\partial D_j} \frac{\partial u}{\partial \nu(j)} \, d\sigma = 0 \quad \text{for } j = 1, 2.
\]

Here and throughout this paper \( \nu(j) \) is the outward unit normal to \( \partial D_j \).

The gradient of the solution \( \nabla u \) represents the electric field (with the opposite sign) in the presence of inclusions and the stress field in two-dimensional antiplane elasticity, and it may become arbitrarily large as the distance between two inclusions tends to 0. It has been proved that the generic rate of the gradient blow up is \( \epsilon^{-1/2} \) in two dimensions \([2, 4, 5, 8, 11, 16, 17]\) and \( |\epsilon \log \epsilon|^{-1} \) in three dimensions \([5, 6, 12, 13, 14, 15]\), where \( \epsilon \) is the distance between two inclusions. Occurrence of

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the gradient blow up depends on the background potential (the harmonic function $H$ in (1.1)), and those background potentials which actually make the gradient blow up are characterized in [3] when $D_1$ and $D_2$ are disks.

The results mentioned above are the gradient estimates of the solution from above and below, namely,

$$\frac{C_1}{\psi(\epsilon)} \leq |\nabla u| \leq \frac{C_2}{\psi(\epsilon)} + C_3$$

for some positive constants $C_1$, $C_2$, and $C_3$, where

$$\psi(\epsilon) = \begin{cases} \sqrt{\epsilon} & \text{if } d = 2, \\ \epsilon \log \frac{1}{\epsilon} & \text{if } d = 3. \end{cases}$$

The constants $C_1$ and $C_2$ can possibly be 0 depending on the background potential $H$.

The interest of this paper lies in the asymptotic behavior of $\nabla u$ as the distance between two inclusions tends to 0. Since the singular behavior of $\nabla u$ occurs in the narrow region in between two inclusions, we are particularly interested in its behavior there. In this regard, a complete characterization of the singular behavior of $\nabla u$ has been obtained when inclusions are disks [10] and strictly convex domains in $\mathbb{R}^2$ [1].

Let $D_1$ and $D_2$ be disks in $\mathbb{R}^2$ of radii $r_1$ and $r_2$, respectively, and let $R_j$ be the reflection with respect to $\partial D_j$, $j = 1, 2$. Then the combined reflections $R_1R_2$ and $R_2R_1$ have unique fixed points, say $f_1 \in D_1$ and $f_2 \in D_2$. Let

$$h(x) = \frac{1}{2\pi} (\log |x - f_1| - \log |x - f_2|)$$

(see section 2 for a discussion on the function $h$). It has been proved that the solution $u$ to (1.1) can be expressed as

$$u(x) = \frac{4\pi r_1 r_2}{r_1 + r_2} (n \cdot \nabla H)(c) h(x) + g(x), \quad x \in \mathbb{R}^2 \setminus (D_1 \cup D_2),$$

where $c$ is the middle point of the shortest line segment connecting $\partial D_1$ and $\partial D_2$, $n$ is the unit vector in the direction of $f_2 - f_1$, and $|\nabla g(x)|$ is bounded independently of $\epsilon$ on any bounded subset of $\mathbb{R}^2 \setminus (D_1 \cup D_2)$. So the singular behavior of $\nabla u$ is completely characterized by $\nabla h$. In particular, it can be shown using (1.6) that the maximal concentration of $\nabla u$ occurs along the shortest line segment connecting $\partial D_1$ and $\partial D_2$, and on that segment

$$\nabla u \approx \frac{2\sqrt{2}}{\sqrt{\epsilon}} \sqrt{\frac{r_1 r_2}{r_1 + r_2}} (n \cdot \nabla H)(c)n.$$
centers. Let \( c \) be the middle point of \( c_1 \) and \( c_2 \), and \( n \) the unit vector in the direction of \( c_2 - c_1 \), i.e.,

\[
c = \frac{c_1 + c_2}{2}, \quad n = \frac{c_2 - c_1}{|c_2 - c_1|}.
\]

Let \( R_j, j = 1, 2 \), be the reflection with respect to \( \partial D_j \), i.e.,

\[
R_j(x) = \frac{r(x - c_j)}{|x - c_j|^2} + c_j,
\]

and let, for \( k = 0, 1, \ldots \),

\[
\begin{cases}
p_{2k} = (R_2R_1)^k c_2, \\ p_{2k+1} = R_2(R_1R_2)^k c_1.
\end{cases}
\]

We emphasize that \( p_n \) is contained in \( D_2 \) and monotonically converges to \( p \) as \( n \to \infty \) where \( p \) is the fixed point of the combined reflection \( R_2R_1 \). Let

\[
\mu_n = \frac{1}{|c_1 - p_n|}, \quad n = 1, 2, \ldots,
\]

and

\[
q_0 = 1 \quad \text{and} \quad q_n = \prod_{j=1}^{n} \mu_j, \quad n \geq 1.
\]

Let \( \rho(x) \) be the distance from \( x \) to the straight line connecting \( c_1 \) and \( c_2 \), i.e.,

\[
\rho(x) = |(x - c) - (x - c, n)n|.
\]

The following is the main result of this paper.

**Theorem 1.1.** Suppose that the radius of the balls is much larger than the distance between them, i.e., \( \epsilon \ll r \). The gradient \( \nabla u \) of the solution to (1.1) can be expressed as

\[
\nabla u(x) = \frac{C_H^\epsilon}{|\log \epsilon| (\epsilon + r\rho(x)^2)} (n + \eta(x)) + \nabla g(x) \quad \text{if } \rho(x) \leq \frac{r}{|\log \epsilon|^2},
\]

where

\[
C_H^\epsilon = 2 \sum_{n=0}^{\infty} q_n (H(p_n) - H(-p_n)),
\]

\( |\nabla g| \) is bounded on any bounded region in \( \mathbb{R}^3 \setminus (D_1 \cup D_2) \) regardless of \( \epsilon \), and

\[
|\eta(x)| \leq C|\log \epsilon|^{-1}
\]

for some constant \( C > 0 \) independent of \( \epsilon \).

Some remarks on Theorem 1.1 are in order. We first observe that the set \( \rho(x) \leq r|\log \epsilon|^{-2} \) where (1.12) holds is a narrow region in between two spheres. The formula (1.12) shows that the major singular term of \( \nabla u \) is in the direction of \( n \), and that the intensity of the field is constant on a level surface where \( \rho(x) = \text{constant} \). Note that
the level surface of $\rho(x)$ is a cylinder around the line connecting the centers of the two spheres. So the intensity of the field decreases radially from the line connecting the centers of the two spheres. The highest concentration of the field occurs when $\rho(x) = 0$, in other words, when $x$ is on the line segment connecting two closest points on the spheres, and on the segment,

$$\nabla u \approx \frac{C_H}{\epsilon|\log \epsilon|} n.$$  

(1.15)

When $H$ is a linear function in the direction of $n$, i.e., $H(x) = E_0(n \cdot x)$, it can be shown that $C_H \approx 2\pi^2 r E_0 / 3$, which is the constant appearing in the expression of the average field given in (35) of [12]. See our Remark 5.1 at the end of section 5 for a precise description of this.

Note that $C_H$ depends on $\epsilon$ since $p_n$ and $q_n$ do. The following theorem reveals the limiting behavior of $C_H$ as $\epsilon \to 0$.

**Theorem 1.2.** We have

$$C_H = C_H + O(\sqrt{\epsilon}|\log \epsilon|) \quad \text{as} \quad \epsilon \to 0,$$

(1.16)

where

$$C_H = 2 \sum_{n=1}^{\infty} \frac{1}{n} \left( H \left( \frac{r}{n} n + c \right) - H \left( -\frac{r}{n} n + c \right) \right).$$

(1.17)

In particular, if $\rho(x) = 0$, then

$$\lim_{\epsilon \to 0} \epsilon|\log \epsilon||\nabla u(x)| = |C_H|.$$  

(1.18)

We emphasize that the occurrence of the gradient blow up depends on the constant $C_H$: if $C_H \neq 0$, then it occurs. If $C_H = 0$, then either $|\nabla u|$ is bounded or the blow up rate is weaker than the generic rate $(\epsilon|\log \epsilon|)^{-1}$. One can show, for example, that if the centers of the balls lie on the $x$-axis and their middle point is $(0,0,0)$, and if $H(x,y,z) = x^3 - 3xy^2$, then $C_H \neq 0$, and hence $|\nabla u|$ blows up as $\epsilon \to 0$ in spite of $(n \cdot \nabla H)(0,0,0) = 0$. It is interesting to observe that this is in contrast with the two-dimensional case of disks. In view of (1.7), the blow up occurs only when $(n \cdot \nabla H)(0,0) \neq 0$ (assuming $c = (0,0)$). So, $\nabla u(x,y)$ blows up in two dimensions only when the background potential $H$ has the linear term $n \cdot x$.

The main ingredient in deriving (1.12) is the singular function $h$, which is the solution to

$$\begin{cases} 
\Delta h = 0 & \text{in } \mathbb{R}^d \setminus \overline{D_1 \cup D_2}, \\
h = \text{constant} & \text{on } \partial D_j, \ j = 1,2, \\
\int_{\partial D_j} \frac{\partial h}{\partial \nu^{(j)}} \ ds = (-1)^{j+1}, & j = 1,2, \\
h(x) = O(|x|^{1-d}) & \text{as } |x| \to \infty.
\end{cases}$$

(1.19)

Such a solution exists and is unique (see [1, 16]). We emphasize that the constant values of $h$ on $\partial D_1$ and on $\partial D_2$ are different, and because of that, the gradient of $h$ becomes arbitrarily large if the distance between $D_1$ and $D_2$ is small. This function characterizes the singular behavior of the solution to (1.1). In fact, if we define the
function \( g \) by
\[
(1.20) \quad u(x) = \frac{u_{|\partial D_2} - u_{|\partial D_1}}{h_{|\partial D_2} - h_{|\partial D_1}} h(x) + g(x), \quad x \in \mathbb{R}^d \setminus (D_1 \cup D_2),
\]
then one can see that \( g \) is harmonic in \( \mathbb{R}^d \setminus \overline{D_1 \cup D_2} \) and \( g_{|\partial D_1} = g_{|\partial D_2} \); in other words, there is no potential difference of \( g \) on \( \partial D_1 \) and \( \partial D_2 \). So it can be shown in the same way as in [10] that \( |\nabla g| \) is bounded on any bounded subsets of \( \mathbb{R}^d \setminus (D_1 \cup D_2) \). It means that the singular behavior of \( \nabla u \) is completely determined by \( h \) (and the background potential \( H \)).

The function \( h \) was first introduced in [16] and used in a crucial way to derive estimates for the gradient blow up in [15, 16, 17]. It is worth mentioning that \( (\frac{\partial h}{\partial \nu(1)}, \frac{\partial h}{\partial \nu(2)}) \) is an eigenvector corresponding to the eigenvalue \( 1/2 \) of the Neumann–Poincaré operator associated with the interface problem (1.1) as shown in [1, 7].

If \( D_1 \) and \( D_2 \) are disks, then \( h \) is given by (1.5). In fact, \( \partial D_1 \) and \( \partial D_2 \) are the Apollonian circles of the fixed points \( f_1 \) and \( f_2 \), and hence \( |x - f_1|/|x - f_2| \) is constant on \( \partial D_1 \) and \( \partial D_2 \). It is worth emphasizing that here the radii of disks may be different. If \( D_1 \) and \( D_2 \) are spheres, it has been proved in [15] that \( h \) is given by a weighted sum of the difference of the point charges: let \( \Gamma(x) = \frac{1}{4\pi} |x|^{-1} \), the fundamental solution of the Laplacian in three dimensions. Then the singular function \( h \) is given by
\[
(1.22) \quad h(x) = \frac{1}{\sum_{n=0}^{\infty} q_n} \sum_{n=0}^{\infty} q_n (\Gamma(x - p_n) - \Gamma(x + p_n)).
\]

This formula has been used in [15] to derive estimates like (1.3). We emphasize that in [15] an upper bound for \( h \) is derived in a more general case when the radii of spheres are allowed to be different. In this paper we derive finer estimates of \( h \) for the purpose of deriving (1.12).

This paper is organized as follows. In section 2, we review the construction of the singular function in [15]. In section 3, we prove some technical lemmas which are required to estimate the singular function. In section 4, we derive an asymptotic formula of the singular function. In section 5, we prove Theorems 1.1 and 1.2, and we also make a remark on the connection between the results of this paper and those in [12].

2. Singular functions on spheres. Since the radius \( r \) is much larger than \( \epsilon \), we may assume after scaling, if necessary, that \( r = 1 \). We may also assume the centers are on the \( x \)-axis and \( c = (0, 0, 0) \) after rotation and shifting if necessary. We assume so in what follows. It is also convenient to write \( \epsilon = 2\delta \) so that \( c_1 = (-1 - \delta, 0, 0) \) and \( c_2 = (1 + \delta, 0, 0) \). Then, the function \( \rho \) defined in (1.11) becomes
\[
(2.1) \quad \rho(x, y, z) = \sqrt{y^2 + z^2},
\]
and \( n = (1, 0, 0) \). Note that \( p_n \) defined by (1.8) satisfies
\[
(2.2) \begin{cases}
  p_{2k} = (R_2 R_1)^k c_1 = -(R_1 R_2)^k c_2 = R_2 (R_1 R_2)^k c_1 \\
  p_{2k+1} = -R_1 (R_2 R_1)^k c_2 = R_2 (R_1 R_2)^k c_1.
\end{cases}
\]
Define the function $h_1$ by
\begin{equation}
(2.3) \quad h_1(x) := \sum_{k=0}^{\infty} \left( \frac{q_{2k}}{|x + p_{2k}|} - \frac{q_{2k+1}}{|x - p_{2k+1}|} \right).
\end{equation}

Then $h_1$ is harmonic in $\mathbb{R}^3 \setminus \overline{D_1 \cup D_2}$. Since the circle of Apollonius implies
\begin{equation}
(2.4) \quad \frac{|y - c_j||x - R_j(y)|}{|x - y|} = \frac{|x - y|}{|x - c_j|} \quad \text{for } |y - c_j| > 1, \ x \in \partial D_j, \ j = 1, 2,
\end{equation}
we have
\[ \frac{q_{2k+1}}{|x - p_{2k+1}|} = \frac{q_{2k+1}}{|c_1 - p_{2k+1}|} \frac{1}{|x - R_1(p_{2k+1})|} = \frac{q_{2k+2}}{|x + p_{2k+2}|} \]
if $x \in \partial D_1$, and
\[ \frac{q_{2k}}{|x + p_{2k}|} = \frac{q_{2k}}{|c_2 + p_{2k}|} \frac{1}{|x - R_2(-p_{2k})|} = \frac{q_{2k+1}}{|x - p_{2k+1}|} \]
if $x \in \partial D_2$. So we have
\begin{equation}
(2.5) \quad h_1|_{\partial D_1} = 1, \ h_1|_{\partial D_2} = 0.
\end{equation}

Moreover, since
\[ \frac{1}{4\pi} \int_{\partial D_j} \frac{\partial}{\partial \nu} \left( \frac{1}{|x - y|} \right) d\sigma(x) = \begin{cases} -1 & \text{if } y \in D_j, \\ 0 & \text{if } y \notin D_j, \end{cases} \]
we have
\begin{equation}
(2.6) \quad \frac{1}{4\pi} \int_{\partial D_1} \frac{\partial h_1}{\partial \nu} d\sigma = -\sum_{k=0}^{\infty} q_{2k}, \quad \frac{1}{4\pi} \int_{\partial D_2} \frac{\partial h_1}{\partial \nu} d\sigma = \sum_{k=0}^{\infty} q_{2k+1}.
\end{equation}

Define $h_2$ by
\begin{equation}
(2.7) \quad h_2(x) := \sum_{k=0}^{\infty} \left( \frac{q_{2k}}{|x - p_{2k}|} - \frac{q_{2k+1}}{|x + p_{2k+1}|} \right).
\end{equation}

Then $h_2$ is harmonic in $\mathbb{R}^3 \setminus \overline{D_1 \cup D_2}$, and one can show similarly that
\begin{equation}
(2.8) \quad h_2|_{\partial D_1} = 0, \ h_2|_{\partial D_2} = 1
\end{equation}
and
\begin{equation}
(2.9) \quad \frac{1}{4\pi} \int_{\partial D_1} \frac{\partial h_2}{\partial \nu} d\sigma = \sum_{k=0}^{\infty} q_{2k+1}, \quad \frac{1}{4\pi} \int_{\partial D_2} \frac{\partial h_2}{\partial \nu} d\sigma = -\sum_{k=0}^{\infty} q_{2k}.
\end{equation}

It then follows from (2.5), (2.6), (2.8), and (2.9) that the solution to (1.19) is given by
\begin{equation}
(2.10) \quad h(x) := -\frac{1}{4\pi} \sum_{n=0}^{\infty} q_n \left( h_1(x) - h_2(x) \right) = \frac{1}{4\pi} \sum_{n=0}^{\infty} q_n \sum_{n=0}^{\infty} q_n \left( \frac{1}{|x - p_n|} - \frac{1}{|x + p_n|} \right).
\end{equation}

Thus we have (1.22). We also have
\begin{equation}
(2.11) \quad h|_{\partial D_2} - h|_{\partial D_1} = \frac{2}{4\pi} \sum_{n=0}^{\infty} q_n.
\end{equation}

In the next section we derive fine properties of the sequences $p_n$ and $q_n$, which are used in deriving an asymptotic formula for $h$. 
3. Properties of the sequences $p_n$ and $q_n$. Let $p = (p, 0, 0)$ be the fixed point of the combined reflection $R_2R_1$ as before. Then one can easily see that $p$ satisfies

$$ p = \frac{1}{1 + \delta + p} + 1 + \delta, $$

so that

$$ p = \sqrt{2\delta} + O(\delta) \quad \text{as } \delta \to 0. $$

Let $p_n = (p_n, 0, 0)$. Then $p_0 = 1 + \delta$, and $p_n$ satisfies the recursive relations

$$ p_{n+1} = \frac{1}{1 + \delta + p_n} + 1 + \delta, \quad n = 0, 1, \ldots. $$

One can further see that

$$ p_n = p \left( \frac{2}{A^{n+1} - 1} + 1 \right) = p \left( \frac{A^{n+1} + 1}{A^{n+1} - 1} \right), $$

where

$$ A := \frac{1 + \delta + p}{1 + \delta - p}. $$

Note that

$$ A = 1 + 2p + O(\delta) = 1 + 2\sqrt{2\delta} + O(\delta). $$

In particular, the sequence $p_n$ is decreasing and converges to $p$ as $n \to \infty$.

Since

$$ \mu_n = \frac{1}{|c_1 - p_n|} = \frac{1}{1 + \delta + p_n} = (1 + \delta - p_{n+1}), $$

we have

$$ q_{n+1} = \mu_n q_n = \frac{1}{1 + \delta + p_n} q_n = (1 + \delta - p_{n+1}) q_n. $$

For a given $\delta > 0$, let $N_0 = N_0(\delta)$, $N = N(\delta)$, and $N_1 = N_1(\delta)$ be as follows:

$$ N_0(\delta) = \lceil \log \delta \rceil, \quad N(\delta) = \left\lfloor \frac{1}{\sqrt{\delta}} \right\rfloor, \quad N_1(\delta) = \left\lceil \frac{1}{\delta |\log \delta|} \right\rceil. $$

Here $\lceil \cdot \rceil$ is the Gaussian bracket. We use this notation for the rest of this paper. Since $\delta$ is sufficiently small, we have

$$ N_0(\delta) \ll N(\delta) \ll N_1(\delta). $$

The following lemma was obtained in [15].

**Lemma 3.1.** There is a constant $C$ independent of $\delta$ such that

$$ \left| p_n - \frac{1}{n+1} \right| + \left| q_n - \frac{1}{n+1} \right| \leq C\sqrt{\delta} $$
and

\[ |p_n - p_{n+1}| < \frac{C}{n^2} \]

for \( n \leq N(\delta) \).

We prove the following lemma.

**Lemma 3.2.** Let \( N = N(\delta) \) and \( N_1 = N_1(\delta) \) as before.

(i) There is a positive \( C \) independent of \( \delta \) such that

\[ \left| \sum_{n=0}^{\infty} q_n - \sum_{n=1}^{N} \frac{1}{n} \right| \leq C \text{ and } \sum_{n=N}^{\infty} q_n \leq C. \]  

(ii) \( p_n - p \geq 2 \sqrt{\delta} A^{-n} \) for all \( n \).

(iii) There is a constant \( C \) such that \( p_n - p \geq C n \) for all \( n \leq N \).

(iv) \( 0 < p_{N_1} - p \leq e^{-1/(\sqrt{\delta}\log \delta)} \).

**Proof.** Since \( p_n \) decays to \( p \), we have from (3.7) that

\[ q_n \leq (1 + \delta - p)^{n-m} q_m \text{ for all } n \geq m \geq 1. \]  

So, it follows from (3.9) that

\[ \sum_{n=N}^{\infty} q_n \leq \sum_{n=N}^{\infty} q_N (1 + \delta - p)^{n-N} \leq \left( C \sqrt{\delta} + \frac{1}{N+1} \right) \sum_{n=N}^{\infty} (1 + \delta - p)^{n-N} \leq C, \]

and

\[ \left| \sum_{n=0}^{\infty} q_n - \sum_{n=1}^{N} \frac{1}{n} \right| \leq C N \sqrt{\delta} + \sum_{n=N}^{\infty} q_n \leq C. \]

This proves (i).

We have from (3.3) that for each \( n \in \mathbb{N} \),

\[ p_n - p = \frac{2p}{A^{n+1} - 1}. \]  

So, (ii) follows from (3.1).

Now, suppose that \( n \leq N \). Since \( A \leq 1 + 3p \), using the inequality

\[ (1 + s)^n \leq 1 + ns + \frac{1}{2} n^2 s^2 (1 + s)^n, \]

which holds for all \( s > 0 \), we obtain

\[ A^n \leq (1 + 3p)^n \leq 1 + 3np + \frac{9}{2} n^2 p^2 (1 + 3p)^n. \]

Since \( np \leq Np \leq 2 \), and \((1 + t)^{1/t}\) increases to \( e \) as \( t \to 0^+ \), we have

\[ (1 + 3p)^n \leq \left( (1 + 3p)^{\frac{1}{3p}} \right)^{3np} \leq e^6, \]
and hence, from the second inequality in (3.14),

$$A^n \leq 1 + Cnp$$

for some constant $C$ independent of $n \leq N$ and $\delta$. We then infer from (3.3) that

$$p_n - p = \frac{2p}{A^{n+1} - 1} \geq \frac{1}{Cn}, \quad n \leq N(\delta).$$

Now, if $n = N_1$, then we have

$$\log(A^n) = n \log A \geq \frac{n(A - 1)}{2} \geq \frac{1}{\sqrt{\delta} |\log \delta|},$$

and hence

$$A^n \geq e^{\frac{1}{\sqrt{\delta} |\log \delta|}}.$$

Now (iv) follows from (3.13). This completes the proof.  

Lemma 3.2(i) yields

$$\sum_{n=0}^{\infty} q_n = \frac{1}{2} |\log \delta| + O(1). \quad (3.15)$$

The following lemma provides the finer properties of $p_n$ and $q_n$ that are crucial in proving the main result of this paper.

**Lemma 3.3.**

(i) If $N_0(\delta) \leq n \leq N_1(\delta)$, then

$$\frac{q_n}{p_n - p_n + 1} = \frac{1 + O(|\log \delta|^{-1})}{\sqrt{p_n^2 - p^2}} \quad \text{as} \quad \delta \to 0,$$

where $O(|\log \delta|^{-1})$ is independent of $n$.

(ii) There are constants $C_1$ and $C_2$ such that

$$q_n \leq C_1 (1 - p + \delta)^{n - N_1} e^{-\frac{C_2}{\sqrt{\delta} |\log \delta|}} \quad (3.17)$$

for all $n \geq N_1 = N_1(\delta)$.

**Proof.** If $n > m$, then we have from (3.7) that

$$\log q_n = -\sum_{j=m}^{n-1} \log(1 + \delta + p_j) + \log q_m.$$

Using the inequality $|\log(1 + t) - t| \leq Ct^2$, we obtain

$$\log q_n = -\sum_{j=m}^{n-1} p_j - \delta(n - m) + \log q_m + E_1,$$

where the error term $E_1$ satisfies

$$|E_1| \leq C_1 \sum_{j=m}^{n-1} (\delta + p_j)^2 \leq C_2 \sum_{j=m}^{n-1} p_j^2. \quad (3.18)$$
The last inequality above holds since $\delta \ll p < p_j$. Here and in the rest of this proof, the $E_j$’s denote errors to be estimated. We then have from (3.3) that

$$\log \frac{q_n}{q_m} = -(\delta + p)(n - m) - 2p \sum_{j=m+1}^{n} \frac{1}{A^j - 1} + E_1.$$  

Since $\frac{1}{A^j - 1} = \frac{A^{-j}}{1 - A^{-j}}$ is decreasing in $j$, we have

$$\left| \sum_{j=m+1}^{n} \frac{1}{A^j - 1} + \frac{1}{\log A} \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) \right| \leq \sum_{j=m+1}^{n} \frac{A^{-j}}{1 - A^{-j}} - \int_{m+1}^{n+1} \frac{A^{-x}}{1 - A^{-x}} \, dx \leq \frac{A^{-m-1}}{1 - A^{-m-1}}.$$  

So we have

$$\log \frac{q_n}{q_m} = -(\delta + p)(n - m) + \frac{2p}{\log A} \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) + E_2,$$

where the new error term $E_2$ satisfies

$$|E_2| \leq C \left( \sum_{j=m+1}^{n} p_j^2 + pA^{-m-1} \frac{1}{1 - A^{-m-1}} \right).$$

One can see from (3.5) that

$$\frac{2p}{\log A} = 1 + E_3,$$

where

$$|E_3| \leq C\sqrt{\delta}.$$  

So, we have

$$\log \frac{q_n}{q_m} = -(\delta + p)(n - m) + (1 + E_3) \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) + E_2,$$

which in turn implies

$$q_n = q_m e^{-pn} \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) e^{E_4},$$

where

$$E_4 := pn - \delta(n - m) + E_2 + E_3 \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right).$$

Note that

$$p_n - p_{n+1} = (p_{n+1} - p) \frac{A - 1}{1 - A^{-n-1}},$$
so that
\[(3.24) \quad \frac{q_n}{p_n - p_{n+1}} = \frac{q_m e^{-p_m}}{p_{n+1} - p} \frac{1 - A^{-m-1}}{A - 1} e^{E_4}.
\]
Since \(p_n/p = (A^{n+1} + 1)/(A^{n+1} - 1)\), we have
\[(n + 1) \log A = \log \left(\frac{p_n + p}{p_n - p}\right),
\]
and, since \(\log A = 2p + O(\delta)\), it follows that
\[p_n = \frac{1}{2} \log \left(\frac{p_n + p}{p_n - p}\right) + E_5,
\]
where
\[(3.25) \quad |E_5| \leq C(n\delta + \sqrt{\delta}).
\]
We then obtain from (3.24)
\[
\frac{q_n}{p_n - p_{n+1}} = \frac{1}{\sqrt{p_n^2 - p^2}} \frac{1 - A^{-m-1}}{A - 1} e^{E_4 - E_5}
\]
\[(3.26) \quad = \frac{1}{\sqrt{p_n^2 - p^2}} \frac{q_m}{p_n - p} \frac{1 - A^{-m-1}}{A - 1} e^{E_4 - E_5}.
\]
Suppose now that \(m = N_0 - 1\) and \(m < n \leq N_1\). Then we have \(E_5 = O(|\log \delta|^{-1})\).
We will show that
\[
\frac{p_n - p}{p_{n+1} - p} = 1 + O(|\log \delta|^{-1}),
\]
\[(3.27) \quad \frac{1 - A^{-m-1}}{A - 1} = 1 + O(|\log \delta|^{-1}),
\]
\[(3.28) \quad E_4 = O(|\log \delta|^{-1}).
\]
Once we have these estimates, then (i) will follow from (3.26).
To prove (3.27), we first observe that
\[
\frac{p_n - p}{p_{n+1} - p} = \frac{A^{n+2} - 1}{A^{n+1} - 1} = A \left(1 + \frac{1}{A + A^2 + \cdots + A^{n+1}}\right).
\]
Since \(A > 1\), \(n \geq |\log \delta|\), and \(A = 1 + O(\sqrt{\delta})\), we have
\[
\frac{p_n - p}{p_{n+1} - p} = (1 + O(\sqrt{\delta}))(1 + O(|\log \delta|^{-1})) = 1 + O(|\log \delta|^{-1}).
\]
To prove (3.28), we use inequalities
\[(m + 1)s - \frac{1}{2} m(m + 1)s^2 \leq 1 - (1 - s)^{m+1} \leq (m + 1)s,
\]
which hold for all \(s \in [0, 1]\). Since \(A^{-1} = 1 - 2p + O(\delta)\), we have
\[(m + 1)(2p + O(\delta)) - \frac{1}{2} m(m + 1)(2p + O(\delta))^2 \leq 1 - A^{-m-1} \leq (m + 1)(2p + O(\delta)).
\]
Since \( m = O(|\log \delta|) \) and \( p = O(\sqrt{\delta}) \), we have

\[
1 - A^{-m-1} = 2(m + 1)p + O(\delta|\log \delta|^2).
\]

Note that

\[
\frac{1}{A - 1} = \frac{1}{2p + O(\delta)} = \frac{1}{2p} + O(1).
\]

Since \( q_m = \frac{1}{m+1} + O(\sqrt{\delta}) \) by Lemma 3.1 and \( m = N_0 - 1 \), we infer that

\[
q_m \frac{1 - A^{-m-1}}{A - 1} = \left( \frac{1}{m+1} + O(\sqrt{\delta}) \right) (2(m + 1)p + O(\delta|\log \delta|^2)) \left( \frac{1}{2p} + O(1) \right)
\]

\[
= 1 + O(|\log \delta|^{-1}).
\]

So, (3.28) is proved.

To prove (3.29), we first estimate \( E_2 \). We have from (3.9) that

\[
\sum_{j=m+1}^{n} p_j^2 \leq C \sum_{j=N_0}^{N} p_j^2 + \sum_{j=N+1}^{N_1} p_j^2
\]

\[
\leq C \sum_{j=N_0}^{N} \frac{1}{j^2} + \sum_{N}^{N_1} p_N^2
\]

\[
\leq C \left( \frac{1}{N_0} + p_N^2 N_1 \right) = O(|\log \delta|^{-1}).
\]

On the other hand, it follows from (3.30) that

\[
\frac{pA^{-m-1}}{1 - A^{-m-1}} = \frac{p + O(\delta|\log \delta|)}{2(m + 1)p + O(\delta|\log \delta|^2)}
\]

\[
= \frac{1}{2(m + 1)} \left( 1 + O(\sqrt{\delta}|\log \delta|) \right) = O(|\log \delta|^{-1}).
\]

So we infer from (3.19) that

\[
E_2 = O(|\log \delta|^{-1}).
\]

Since \( p = O(\sqrt{\delta}) \), we obtain from (3.30) that

\[
1 \geq \frac{1 - A^{-m-1}}{1 - A^{n-1}} \geq 1 - A^{-m-1} \geq C \sqrt{\delta}|\log \delta|.
\]

We then infer from (3.21) that

\[
\left| E_3 \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) \right| \leq C \sqrt{\delta}|\log \delta|.
\]

Thus we have from (3.23), (3.31), and (3.32) that

\[
|E_4| \leq |pm| + \delta(n - m) + |E_2| + \left| E_3 \log \left( \frac{1 - A^{-m-1}}{1 - A^{-n-1}} \right) \right|
\]

\[
\leq C \left( \sqrt{\delta}|\log \delta| + |\log \delta|^{-1} \right) \leq C|\log \delta|^{-1},
\]

and thus (3.29) is proved.
We have from (3.22) that
\[ q_{N_i} = q_m e^{-p N_i} \left( \frac{1 - A^{-m-1}}{1 - A^{-N_i-1}} \right) e^{E_i}. \]
So, it follows from (3.29) that
\[ q_{N_i} \leq C_1 e^{-\sqrt{\delta} \log n} \]
for some constants $C_1$ and $C_2$. Now, (ii) follows from (3.12). This completes the proof. \(\square\)

4. Asymptotic behavior of the singular function. Let
\[ (4.1) \quad R_\delta := \{ \mathbf{x} \in \mathbb{R}^3 \setminus (D_1 \cup D_2) \mid \rho(\mathbf{x}) \leq |\log \delta|^{-1} \}, \]
where $\rho$ is given by (2.1). Note that $R_\delta$ is a narrow region in between $D_1$ and $D_2$. Let
\[ (4.2) \quad v(\mathbf{x}) := \left( 4\pi \sum_{n=0}^{\infty} q_n \right) h(\mathbf{x}) = \sum_{n=0}^{\infty} q_n \left( \frac{1}{|\mathbf{x} - \mathbf{p}_n|} - \frac{1}{|\mathbf{x} + \mathbf{p}_n|} \right). \]
In this section we investigate the asymptotic behavior of $\nabla v(\mathbf{x})$ in the region $R_\delta$. We obtain the following proposition.

**Proposition 4.1.** For $\mathbf{x} = (x, y, z) \in R_\delta$, we have
\[ (4.3) \quad \nabla v(\mathbf{x}) = \frac{2}{2\delta + \rho(\mathbf{x})^2} \left( (1, 0, 0) + O(|\log \delta|^{-1}) \right). \]
It turns out that $|\partial_y v(\mathbf{x})|$ and $|\partial_z v(\mathbf{x})|$ can be estimated without much difficulty. In fact, we obtain the following lemma, whose proof is given in subsection 4.1.

**Lemma 4.2.** For $\mathbf{x} = (x, y, z) \in R_\delta$, we have
\[ (4.4) \quad |\partial_y v(\mathbf{x})| + |\partial_z v(\mathbf{x})| \leq \frac{C}{\sqrt{\delta} + \rho(\mathbf{x})} \left( 1 + \log \left( 1 + \frac{\rho(\mathbf{x})^2}{\delta} \right) \right) \]
for some constant $C$ independent of $\delta$.

Estimates of $\partial_y v(\mathbf{x})$, especially those terms for $N_0 \leq n \leq N_1$, are quite involved. Based on Lemma 3.3(i), we compare $v$, which is given as an infinite series, with the integral defined by
\[ (4.5) \quad v_0(\mathbf{x}) := \int_{-p}^{1} \left( \frac{1}{|\mathbf{x} - (t, 0, 0)|} - \frac{1}{|\mathbf{x} + (t, 0, 0)|} \right) \frac{1}{\sqrt{t^2 - p^2}} \, dt, \]
where $(p, 0, 0)$ is the fixed point of the combined reflections $R_2R_1$. We obtain the following lemmas, whose proofs are given in subsections 4.2 and 4.3, respectively.

**Lemma 4.3.** For $\mathbf{x} = (x, y, z) \in R_\delta$, we have
\[ (4.6) \quad \partial_z v_0(x) = \frac{2}{2\delta + \rho(\mathbf{x})^2} \left( 1 + O(|\log \delta|^{-1}) \right). \]
**Lemma 4.4.** For $\mathbf{x} = (x, y, z) \in R_\delta$, we have
\[ (4.7) \quad \partial_x v(x) = \partial_x v_0(x) \left( 1 + O(|\log \delta|^{-1}) \right). \]
Proposition 4.1 is an immediate consequence of the above lemmas.
4.1. Proof of Lemma 4.2. We first observe that if \( x = (x, y, z) \in R_\delta \), then
\[
|x| \leq 1 + \delta - \sqrt{1 - y^2 - z^2}
\]
and \( \rho \leq \log \delta^{-2} \), and hence
(4.8)
\[
|x| \leq \delta + \rho(x)^2.
\]
Using the notation \( \rho = \rho(x) \), \( v \) can be expressed as
(4.9)
\[
v(x) = \sum_{n=0}^{\infty} q_n \left( \frac{1}{\sqrt{(x - p_n)^2 + \rho^2}} - \frac{1}{\sqrt{(x + p_n)^2 + \rho^2}} \right).
\]
So, it suffices to estimate \( |\partial_\rho v| \). Note that
\[
\partial_\rho \left( \frac{1}{\sqrt{(x - p_n)^2 + \rho^2}} - \frac{1}{\sqrt{(x + p_n)^2 + \rho^2}} \right) = -\rho \left[ (x - p_n)^2 + \rho^2 \right]^{3/2} + \left[ (x + p_n)^2 + \rho^2 \right]^{3/2}
\]
\[
= 3\rho \int_{-x}^{x} \frac{t - p_n}{(t - p_n)^2 + \rho^2} \, dt.
\]
Therefore, we have
\[
|\partial_\rho \left( \frac{1}{\sqrt{(x - p_n)^2 + \rho^2}} - \frac{1}{\sqrt{(x + p_n)^2 + \rho^2}} \right)| \leq 3\rho \int_{-x}^{x} \frac{1}{(t - p_n)^2 + \rho^2} \, dt.
\]
By (4.8) we have
(4.10)
\[
(t - p_n)^2 + \rho^2 \geq C(\rho^2 + p_n^2)
\]
for some constant \( C \). It then follows that
\[
|\partial_\rho \left( \frac{1}{\sqrt{(x - p_n)^2 + \rho^2}} - \frac{1}{\sqrt{(x + p_n)^2 + \rho^2}} \right)| \leq C\rho(\rho^2 + \delta)\rho^2 + p_n^2 \leq C \frac{\rho}{\rho^2 + p_n^2}.
\]
So we have
\[
|\partial_\rho v(x)| \leq C \sum_{n=0}^{\infty} \frac{\rho q_n}{\rho^2 + p_n^2}.
\]
Let \( N = N(\delta) \). Using Lemma 3.1, we have
\[
\sum_{n=0}^{N-1} \frac{\rho q_n}{\rho^2 + p_n^2} \leq C \sum_{n=1}^{N} \frac{\rho}{(1/n^2 + \rho^2)} \frac{1}{n}
\]
\[
\leq C \sum_{n=1}^{N} \frac{\rho m}{1 + \rho^2 n^3} \leq C \left( 1 + \int_{1}^{1/\sqrt{\delta}} \frac{\rho s}{1 + \rho^2 s^2} \, ds \right)
\]
\[
\leq C \frac{1}{\rho + \sqrt{\delta}} \left( 1 + \log \left( 1 + \frac{\rho^2}{\delta} \right) \right).
\]
If \( n \geq N \), then \( q_n = O(\sqrt{\delta}) \), and thus we have from (3.12) that
\[
\sum_{n=N}^{\infty} \frac{\rho q_n}{\rho^2 + p_n^2} \leq C \sum_{n=N}^{\infty} \frac{\rho}{\rho^2 + \delta} \sqrt{\delta(1 + \delta - p)^{n-N}} \leq \frac{C}{\rho + \sqrt{\delta}}.
\]
This completes the proof. \( \square \)
4.2. Proof of Lemma 4.3. Let

$$\partial_x v_0(x) = \int_p^{\log \delta_{-1}} + \int_{\log \delta_{-1}}^1 \partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \frac{1}{\sqrt{t^2 - \rho^2}} \, dt$$

$$:= I + II.$$

If $|\log \delta_{-1}| \leq t \leq 1$, then $|x \pm (t, 0, 0)| \geq Ct$ for some constant $C$ and for all $x \in \mathbb{R}^3 \setminus (D_1 \cup D_2)$. Since $p = O(\sqrt{\delta})$, we also have $\sqrt{t^2 - \rho^2} \geq Ct$. Thus we have

$$|II| \leq C \int_{|\log \delta_{-1}|}^1 \frac{1}{t^3} \, dt \leq C|\log \delta|^2. \tag{4.11}$$

Suppose now that $p \leq t \leq |\log \delta_{-1}|$. Using (4.8) and the fact that $p = O(\sqrt{\delta})$ again, we have for all $x \in R_\delta$,

$$|tx| \leq t(|\rho^2 + \delta| \leq \frac{C}{|\log \delta|}(t^2 + \rho^2), \tag{4.12}$$

$$|x| \leq (\rho^2 + \delta)^2 \leq \frac{C}{|\log \delta|}(t^2 + \rho^2) \tag{4.13}$$

for some constant $C$ independent of $\delta$. Thus, we have

$$\frac{1}{|x \pm (t, 0, 0)|^3} = \frac{1}{((x \pm t)^2 + \rho^2)^{3/2}} = \frac{1}{(t^2 + \rho^2 \pm 2xt + x^2)^{3/2}}$$

$$= \frac{1}{(t^2 + \rho^2)^{3/2}} (1 + O(|\log \delta|^{-1})). \tag{4.14}$$

From the mean value property, we have

$$\left| \frac{-1}{|x - (t, 0, 0)|^3} + \frac{1}{|x + (t, 0, 0)|^3} \right|
= \left| \frac{1}{((t^2 + x^2 + \rho^2) - 2xt)^{3/2}} - \frac{1}{((t^2 + x^2 + \rho^2) + 2xt)^{3/2}} \right|
\leq \frac{6|xt|}{|t^2 + x^2 + \rho^2| - |2xt|^5/2}. \tag{4.15}$$

It then follows from (4.12) and (4.13) that

$$\left| x \left( \frac{-1}{|x - (t, 0, 0)|^3} + \frac{1}{|x + (t, 0, 0)|^3} \right) \right| \leq C|\log \delta|^{-1} \frac{t}{(t^2 + \rho(x)^2)^{3/2}} \tag{4.16}$$

for some constant $C$ independent of $\delta$.

Since

$$\partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right)
= \frac{x - t}{|x - (t, 0, 0)|^3} + \frac{x + t}{|x + (t, 0, 0)|^3}
= t \left( \frac{1}{|x - (t, 0, 0)|^3} + \frac{1}{|x + (t, 0, 0)|^3} \right) + x \left( \frac{-1}{|x - (t, 0, 0)|^3} + \frac{1}{|x + (t, 0, 0)|^3} \right), \tag{4.17}$$
we obtain from (4.14) and (4.16) that
\[
\partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) = \frac{t}{(t^2 + \rho^2)^{3/2}} \left( 2 + O \left( \log \delta \right)^{-1} \right).
\]
It then follows that
\[
I = \left( 2 + O \left( \log \delta \right)^{-1} \right) \int_{\rho}^{\log \delta^{-1}} \frac{t}{(t^2 + \rho^2)^{3/2}} \frac{1}{\sqrt{t^2 - \rho^2}} \, dt.
\]
Using the substitution \( t = \sqrt{t^2 - \rho^2} \), one can see that
\[
\int_{\rho}^{\log \delta^{-1}} \frac{t}{(t^2 + \rho^2)^{3/2}} \frac{1}{\sqrt{t^2 - \rho^2}} \, dt = \frac{1}{\rho^2 + \rho^2} \left( \log \delta^{-1} - \rho^2 \right)^{1/2}.
\]
Since \( \rho = \sqrt{2\delta + O(\delta)} \) and \( \rho \leq \log \delta^{-2} \), we have
\[
\frac{1}{\rho^2 + \rho^2} \left( \log \delta^{-1} - \rho^2 \right)^{1/2} = \frac{1}{2\delta + \rho^2} \left( 1 + O \left( \log \delta \right)^{-1} \right),
\]
and hence
\[
I = \frac{2}{2\delta + \rho^2} \left( 1 + O \left( \log \delta \right)^{-1} \right),
\]
which, together with (4.11), yields
\[
\partial_x v_0(x) = \frac{2}{2\delta + \rho^2} \left( 1 + O \left( \log \delta \right)^{-1} \right) + O(\log \delta^2).
\]
Since \( \rho \leq \log \delta^{-2} \), the above formula can be written as
\[
\partial_x v_0(x) = \frac{2}{2\delta + \rho^2} \left( 1 + O \left( \log \delta \right)^{-1} \right).
\]
This completes the proof. \( \square \)

4.3. Proof of Lemma 4.4. Let \( N_0 = \lfloor \log \delta \rfloor \) and \( N_1 = \lfloor \frac{1}{\log \delta} \rfloor \) as before. Let
\[
\partial_x v(x) = \sum_{n=0}^{N_0-1} \sum_{n=N_0}^{N_1-1} \sum_{n=N_1}^{\infty} \partial_x \left( \frac{1}{|x - p_n|} - \frac{1}{|x + p_n|} \right) q_n
\]
\[
:= S_1(x) + S_2(x) + S_3(x)
\]
and
\[
\partial_x v_0(x) = \int_{p_{N_0}}^{1} \int_{p_{N_1}}^{p_{N_0}} \int_{p_{N_1}}^{p_{N_1}} \partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \frac{1}{\sqrt{t^2 - \rho^2}} \, dt
\]
\[
:= I_1 + I_2 + I_3.
\]
We first estimate \( S_1, S_3, I_1, \) and \( I_3 \). There is a constant \( C > 0 \) independent of \( n \) such that \( |x \pm p_n| \geq Cp_n \) for all \( x \in R_\delta \). So we have from (3.9) that
\[
|S_1(x)| \leq \sum_{n=0}^{N_0-1} \left| \nabla \left( \frac{1}{|x - p_n|} - \frac{1}{|x + p_n|} \right) q_n \right|
\]
\[
\leq C \sum_{n=1}^{N_0-1} n^2 \frac{1}{n} \leq C |\log \delta|^2.
\]
We also have from Lemma 3.3(ii) that
\[
|S_3(x)| \leq \sum_{n=N_1}^{\infty} \left| \nabla \left( \frac{1}{|x - p_n|} - \frac{1}{|x + p_n|} \right) q_n \right| \leq \sum_{n=N_1}^{\infty} \frac{1}{p^n} q_n
\]
\[
\leq C \sum_{n=N_1}^{\infty} \frac{1}{\delta} (1 - p + \delta) e^{-C_2 \sqrt{\delta / \log \delta}} \leq C.
\]

Similarly, we have
\[
|I_1(x)| \leq \frac{1}{p} \left| \nabla \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \right| \frac{1}{\sqrt{t^2 - p^2}} dt
\]
\[
\leq C \int_{-\log \delta}^{-1} \frac{1}{t^3} dt \leq C |\log \delta|^2,
\]
and by Lemma 3.2(iv),
\[
|I_3(x)| \leq \frac{1}{\delta^{5/4}} \frac{1}{\sqrt{t - p}} dt \leq C \frac{1}{\delta^{5/4} e^{1/(2 \sqrt{\delta} |\log \delta|)}} \leq C.
\]

So far, we showed that
\[
|S_1| + |S_3| + |I_1| + |I_3| \leq C |\log \delta|^2.
\]
We set
\[
\tilde{S}_2(x) = \sum_{n=N_0}^{N_1 - 1} \partial_x \left( \frac{1}{|x - p_n|} - \frac{1}{|x + p_n|} \right) \frac{p_n - p_{n+1}}{\sqrt{p_n^2 - p^2}}
\]
and shall prove
\[
|\tilde{S}_2(x) - I_2(x)| \leq C \frac{1}{\sqrt{\delta + \rho}}.
\]
Let us first show that Lemma 4.4 follows from (4.18) and (4.19). We observe from Lemma 3.3(i) that
\[
S_2(x) = \tilde{S}_2(x) \left( 1 + O(|\log \delta|^{-1}) \right).
\]
So we have
\[
\partial_x v = S_1 + S_2 + S_3
\]
\[
= \tilde{S}_2 \left( 1 + O(|\log \delta|^{-1}) \right) + S_1 + S_3
\]
\[
= I_2 \left( 1 + O(|\log \delta|^{-1}) \right) + (\tilde{S}_2 - I_2) \left( 1 + O(|\log \delta|^{-1}) \right) + S_1 + S_3
\]
\[
= \partial_x v_0 \left( 1 + O(|\log \delta|^{-1}) \right) + R,
\]
where
\[
R = -(I_1 + I_3) \left( 1 + O(|\log \delta|^{-1}) \right) + (\tilde{S}_2 - I_2) \left( 1 + O(|\log \delta|^{-1}) \right) + S_1 + S_3.
\]
Since \( \rho \leq |\log \delta|^{-2} \), one can see from (4.18) and (4.19) that
\[
|R| \leq C \left( |\log \delta|^2 + \frac{1}{\sqrt{\delta} + \rho} \right).
\]

Thanks to (4.6), we now have
\[
\partial_x v = \partial_x v_0 \left( 1 + O(|\log \delta|^{-1}) \right) + R = \partial_x v_0 \left( 1 + O(|\log \delta|^{-1}) \right) ,
\]
which we aim to prove.

The rest of this subsection is devoted to the proof of (4.19). For \( N_0 \leq n \leq N_1 \), let
\[
\gamma_n(x) := \left| \partial_x \left( \frac{1}{|x - (p_n, 0, 0)|} - \frac{1}{|x + (p_n, 0, 0)|} \right) \frac{p_n - p_{n+1}}{\sqrt{p_n^2 - p^2}} - \int_{p_{n+1}}^{p_n} \partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \frac{1}{\sqrt{t^2 - p^2}} \, dt \right| .
\]

Let
\[
f(t) := \partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \frac{1}{\sqrt{t^2 - p^2}} .
\]

By the mean value property, there is \( t_n \in [p_{n+1}, p_n] \) such that
\[
f(p_n)(p_n - p_{n+1}) - \int_{p_{n+1}}^{p_n} f(t) \, dt = \frac{f(t_n)}{2}(p_n - p_{n+1})^2 .
\]

So we have
\[
\gamma_n(x) \leq \frac{1}{2} \left| \partial_t \partial_x \left( \frac{1}{|x - (t, 0, 0)|} - \frac{1}{|x + (t, 0, 0)|} \right) \right|_{t=t_n} \frac{1}{\sqrt{t_n^2 - p^2}} (p_n - p_{n+1})^2
\]
\[
+ \frac{1}{2} \left| \partial_x \left( \frac{1}{|x - (t_n, 0, 0)|} - \frac{1}{|x + (t_n, 0, 0)|} \right) \right| \frac{t_n}{(t_n^2 - p^2)^{3/2}} (p_n - p_{n+1})^2
\]
\[
:= \frac{1}{2}(\gamma_{n1}(x) + \gamma_{n2}(x)).
\]

Using (4.8), one can show that
\[
|x \pm (t_n, 0, 0)|^2 \geq C(\rho^2 + t_n^2), \quad x \in R_\delta,
\]
for some constant independent of \( n \). So we have
\[
\gamma_{n1} \leq \frac{C}{\rho^4 + t_n^4} \frac{1}{\sqrt{t_n^2 - p^2}} (p_n - p_{n+1})^2
\]
and
\[
\gamma_{n2} \leq \frac{C}{\rho^2 + t_n^2} \frac{t_n}{(t_n^2 - p^2)^{3/2}} (p_n - p_{n+1})^2.
\]
If \( n \leq N = \left[ \frac{\delta}{\sqrt{\delta}} \right] \), then we have \( t_n \approx 1/n \) and \( |p_n - p_{n+1}| < C/n^2 \) by Lemma 3.1, and \( p_n - p \geq C/n \) by Lemma 3.2(iii). So, we have

\[
\sum_{n=N_0}^{N} \gamma_{n1} \leq C \sum_{n=N_0}^{N} \frac{1}{(1/n^3 + \rho^3 \sqrt{1/n^2})} \frac{1}{n^4} \leq C \sum_{n=1}^{N} \frac{1}{1 + \rho^3 n^3}.
\]

Note that if \( \rho \leq \delta \), then

\[
\sum_{n=1}^{N} \frac{1}{1 + \rho^3 n^3} \leq N \leq \frac{1}{\sqrt{\delta}},
\]

while if \( \rho > \sqrt{\delta} \), then

\[
\sum_{n=1}^{N} \frac{1}{1 + \rho^3 n^3} \leq \frac{1}{\rho^3} \sum_{n=1}^{N} \frac{1}{n^3} \leq \frac{C}{\rho}.
\]

So, we have

\[
\sum_{n=N_0}^{N} \gamma_{n1} \leq \frac{C}{\sqrt{\delta} + \rho}.
\]

If \( N \leq n \leq N_1 \), we have from (3.3) that

\[
0 \leq p_n - p_{n+1} = 2p(1 - A_n^{-1}) \leq C_2 \delta A_n^{-1},
\]

and by Lemma 3.2(ii), \( p_n - p \geq C\sqrt{\delta} A_n^{-n} \). Since \( p_n > p \) for all \( n \), we have

\[
\sum_{n=N_1}^{N_1-1} \gamma_{n1} \leq C \sum_{n=N_1}^{N_1-1} \frac{1}{(p^3 + \rho^3 \sqrt{p_{n+1} - p^2}) (p_n - p_{n+1})^2} \\
\leq C \sum_{n=N_1}^{\infty} \frac{1}{(\delta^{3/2} + \rho^3) \delta^{1/2} A_n^{-n/2} \delta^2 A^{-2n}} \\
\leq C \sum_{n=N_1}^{\infty} \frac{1}{\delta^{1/2} (\delta^{3/2} + \rho^3) \delta^2 A^{-3/2} n} \\
\leq C \frac{\delta^{3/2}}{\delta^{3/2} + \rho^3} \frac{1}{\sqrt{\delta}} \leq \frac{C}{\sqrt{\delta} + \rho}.
\]

Thus, we have

\[
\sum_{n=N_0}^{N_1} \gamma_{n1} \leq \frac{C}{\rho + \sqrt{\delta}}.
\]

Similarly, one can show that

\[
\sum_{n=N_0}^{N_1} \gamma_{n2} \leq \frac{C}{\rho + \sqrt{\delta}}.
\]

This completes the proof of (4.19).
5. Proofs of Theorems 1.1 and 1.2, and a remark. Now we are ready to prove the main results of this paper.

Proof of Theorem 1.1. It is helpful to recall that $\epsilon = 2\delta$. We have from (1.20) and (2.11) that

$$u = \frac{u|_{\partial D_1} - u|_{\partial D_2}}{h|_{\partial D_1} - h|_{\partial D_2}} h + g$$

$$= \frac{1}{2}(u|_{\partial D_2} - u|_{\partial D_1}) \left(4\pi \sum_{n=0}^{\infty} q_n\right) h + g$$

$$= \frac{1}{2}(u|_{\partial D_2} - u|_{\partial D_1}) v + g.$$  

We emphasize that $|\nabla g|$ is bounded on any bounded subset of $\mathbb{R}^3 \setminus (D_1 \cup D_2)$ regardless of $\delta$, as explained in the introduction. Since $h$ is constant on $\partial D_1$ and $\partial D_2$, one can see from (1.21) and (1.22) that

$$u|_{\partial D_2} - u|_{\partial D_1} = -\int_{\partial(D_1 \cup D_2)} H \frac{\partial h}{\partial \nu} d\sigma$$

$$= -\int_{\partial(D_1 \cup D_2)} H \frac{\partial h}{\partial \nu} d\sigma + \int_{\partial(D_1 \cup D_2)} \frac{\partial H}{\partial \nu} hd\sigma$$

$$= -\sum_{n=0}^{\infty} q_n \sum_{n=0}^{\infty} q_n \int_{\partial(D_1 \cup D_2)} \left[H(x) \frac{\partial}{\partial \nu} (\Gamma(x - p_n) - \Gamma(x + p_n)) - \frac{\partial H}{\partial \nu} (\Gamma(x - p_n) - \Gamma(x + p_n))\right] d\sigma$$

$$= \frac{C_H}{2} \sum_{n=0}^{\infty} q_n.$$  

It then follows from (3.15) that

$$u|_{\partial D_2} - u|_{\partial D_1} = \frac{C_H}{|\log \delta|} \left(1 + O(|\log \delta|^{-1})\right),$$

where $O(|\log \delta|^{-1})$ is independent of $H$. So we obtain from (5.1) that

$$\nabla u = \frac{C_H}{2|\log \delta|} \left(1 + O(|\log \delta|^{-1})\right) \nabla v + \nabla g.$$  

and from (4.3) that

$$\nabla u(x) = \frac{C_H}{|\log \delta|(2\delta + \rho(x))^2} \left((1, 0, 0) + O(|\log \delta|^{-1})\right) + \nabla g(x),$$

and hence (1.12) is proved. This completes the proof. $\square$
Proof of Theorem 1.2. By (3.9), we have for \( n \leq N = N(\delta) \) that

\[
\left| q_n(H(p_n) - H(-p_n)) - \frac{1}{n+1} \left( H \left( \frac{1}{n+1}, 0, 0 \right) - H \left( -\frac{1}{n+1}, 0, 0 \right) \right) \right|
\leq \left| q_n - \frac{1}{n+1} \right| \left| H(p_n) - H(-p_n) \right|
+ \frac{1}{n+1} \left( \left| H(p_n) - H \left( \frac{1}{n+1}, 0, 0 \right) \right| + \left| H(-p_n) - H \left( -\frac{1}{n+1}, 0, 0 \right) \right| \right)
\leq C\sqrt{\delta} \left( \sqrt{\delta} + \frac{1}{n+1} \right) + C\sqrt{\delta} \frac{1}{n+1}.
\]

So we have

\[
\left| \sum_{n=0}^{N-1} q_n(H(p_n) - H(-p_n)) - \sum_{n=1}^{N} \frac{1}{n} \left( H \left( \frac{1}{n}, 0, 0 \right) - H \left( -\frac{1}{n}, 0, 0 \right) \right) \right| \leq C\sqrt{\delta} |\log \delta|.
\]

On the other hand, since \( p_n \) is decreasing, it follows from (3.15) that

\[
\left| \sum_{n=N}^{\infty} q_n(H(p_n) - H(-p_n)) \right| \leq C p_N \sum_{n=N}^{\infty} q_n \leq C\sqrt{\delta} |\log \delta|.
\]

We also have

\[
\left| \sum_{n=N+1}^{\infty} \frac{1}{n} \left( H \left( \frac{1}{n}, 0, 0 \right) - H \left( -\frac{1}{n}, 0, 0 \right) \right) \right| \leq C \sum_{n=N+1}^{\infty} \frac{1}{n^2} \leq C\sqrt{\delta}.
\]

Combining the above estimates, we obtain (1.16).

The formula (1.18) is an immediate consequence of (1.12) and (1.16). This completes the proof.

Remark 5.1. When \( H(x) = E_0(n \cdot x) \) for some constant \( E_0 \), one can see from (1.13) and Theorem 1.2 that

\[
C_H = 4E_0 \sum_{n=0}^{\infty} q_n p_n = 4E_0 \sum_{n=1}^{\infty} \frac{1}{n^2} \left( 1 + O(\sqrt{\delta} |\log \delta|) \right) = \frac{2\pi^2 E_0}{3} \left( 1 + O(\sqrt{\delta} |\log \delta|) \right).
\]

Recall that \( \delta = \epsilon/2 \) assuming that \( r = 1 \). So we have from (5.2) that

\[
(5.4) \quad |u|_{\partial D_2} - |u|_{\partial D_1} = \frac{2\pi^2}{3|\log \epsilon|} E_0 \left( 1 + O(|\log \epsilon|^{-1}) \right).
\]

This is in accordance with the formula (35) in [12]. In fact, it is proved that the average field, which is defined to be the potential difference divided by the distance \( \epsilon \), is given by

\[
(5.5) \quad \frac{|u|_{\partial D_2} - |u|_{\partial D_1}}{\epsilon} = \frac{2\pi^2 r}{3\epsilon (\log \epsilon^2 + 2 \log 2 + 2\gamma)} E_0 \left( 1 + O(|\log \epsilon|^{-1}) \right),
\]

where \( \gamma \) is the Euler constant. Since we assume \( r = 1 \), formulas (5.4) and (5.5) coincide up to \( |\log \epsilon|^{-1} \) for small \( \epsilon > 0 \). It is worth mentioning that the average field for spheres with different radii was also estimated in [13].
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REFERENCES


